TRADABLE PERMIT SYSTEMS FOR A SPATIALLY HETEROGENEOUS EXTERNALITY: A MICROPARAMETER APPROACH

BY

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THESIS

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Abstract

The reduction of surface water flows by adjacent groundwater pumping is an externality caused by agricultural producers. Previous studies have analyzed management policies for such externalities, but these have assumed that the ability to monitor stream depletion is perfect and the ability to regulate it is continuous. In practice, the ability to monitor either stream depletion or groundwater pumping is limited as it is often politically or financially infeasible to do so. Consequently, real-world management strategies result in reductions in farm size rather than in groundwater pumping, an adjustment at the extensive rather than the intensive margin.

To reflect real-world conditions, I consider alternative policies when the ability to monitor is imperfect. The purpose of this analysis is to understand the relative performance of tax, zoning, and trading policies to meet reductions in stream depletion in terms of aggregate costs and changes in industry size. To accomplish this, I develop a microparameter model that considers policies based on easily observable field characteristics, and make a methodological contribution by introducing tradable permit systems into the microparameter framework. Using a Monte Carlo simulation, I derive general results regarding aggregate abatement, industry size, and costs. I then apply this model to a specific case study of a resource district in western Nebraska. Results show that the welfare loss of imperfect monitoring of groundwater pumping may be small. The relative cost-savings of alternative policies depend largely on the joint distribution of field profitability and marginal damage, but the ranking of policies in terms of cost-effectiveness is fairly robust.

To my mother, whose love for her children embodies the movement for environmental protection.

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Introduction and Motivation

Groundwater is an important and reliable source of water for municipal supply, industrial use, and irrigated agriculture. However, the overuse of groundwater can result in increasing pumping costs and shrinking availability of the resource for future generations, as has been the case recently in northwestern Kansas [1]. In other circumstances, groundwater pumping decreases nearby surface water flows, a process known as stream depletion. This outcome affects and inhibits other uses of surface water resources, including several sectors of the economy, recreation, and aquatic ecosystems. In many cases nationally and worldwide, stream depletion has pitted interest groups against one another in fights over water rights.

Climatic variability and population growth have exacerbated these problems, and growing concern for protecting aquatic habitats has been another impetus for the conjunctive management of groundwater and surface water. Interstate litigation reached the Supreme Court regarding such apportionments [2], and more regionally, authorities have taken actions, often controversial, to curb groundwater use for the protection of state- or federally-protected species [3]. These conflicts may even rise to an international level in the near future as understanding of groundwater movement and usage improves [4], [5].

Groundwater management is emerging rapidly in response to these conflicts and has been the topic of many hydrologic and economic studies. It is now well known that many aquifers are hydrologically connected to surface water, and the relationships describing their interactions are improving. Hydrologic science relates a groundwater user's effect on stream depletion; this effect varies through space, dependent on characteristics such as its extraction rate, its distance from the stream, and its surrounding aquifer properties. As such, stream depletion by groundwater pumping is a spatially heterogeneous externality.

However, metering of groundwater extraction in the United States and worldwide is fairly uncommon, making regulatory action challenging. Work to date in the environmental economics literature has explored such problems, called nonpoint source pollution, in which monitoring the direct damage by heterogeneous users is cost prohibitive [6]. Because of this, first-best solutions are often infeasible and regulators are then faced with applying uniform standards. These second-best alternatives may lose efficiency and an important question is by how much, which depends largely on the policy choice and application [7], [8]. There are circumstances under which uniformly applied policies may approximate spatially differentiated policies [7]. Other studies have explored empirically which behavioral or physical proxies approximate first-best solutions [9], [10]. Still, many of these proxies may not be readily observable to the regulator.

When groundwater extraction is not metered, regulators have imperfect information and are limited from using policies that directly target its use. In these cases, management strategies may be discrete rather than continuous. Of the large body of literature on point source and nonpoint source pollution management, the subset of relevant groundwater management literature has assumed that the ability to monitor is perfect and thus the ability to regulate continuous, allowing for spatially targeted policies of groundwater extraction [11], [12], [13], [14]. While perfect monitoring may exist in special circumstances, this is not generally reflective of policies for managing groundwater. As such, the insights gained from this literature, based on continuous regulation, may not be transferable to cases of imperfect information.

Other approaches have more accurately captured the discrete nature of regulations constructed under imperfect monitoring. These are typically referred to as "microparameter" or "putty-clay" models. Still, these analyses compare policies that rely on information that few, if any, regulators possess, such as ambient pollution, input use, and productive output [15], [16], [17]. In the case of groundwater management, stream depletion, groundwater use, and profitability are typically unknown; the lack of this knowledge drives discontinuous regulations such as flat taxes and water retirements. Seemingly, there is a gap in the literature that addresses management in cases with both discontinuous regulations and imperfect monitoring.

In this thesis, I address this gap by comparing alternative policies that are based on more readily observable characteristics. These policies both accurately reflect the regulations for groundwater seen in practice and are readily implementable for regulators with imperfect monitoring. I am interested in finding which of these are most cost-effective, how they affect the industry's size, and the factors driving those results. Further, I explore whether evidence exists that imperfect monitoring leads to significant welfare loss in the case of stream depletion.

The findings presented here show that most of the environmental and economic outcomes of a first-best tax policy, with perfect monitoring, can be achieved with instruments with imperfect monitoring. Further, the magnitude of cost-savings between policies depends largely on firm characteristics, but the relative ranking of policies is much less sensitive to these. The robustness of policy rankings makes it so the choice of policy instrument is unaffected by uncertainty of firm characteristics.

This thesis is presented as follows: in the following section, I present a model of a regulatory environment with imperfect monitoring and discrete choices. I then describe the empirical application of this model to a resources district in western Nebraska, along with the data that enables me to test it. To gain a general understanding of the model, I first compare policy instruments by conducting a Monte Carlo simulation that draws randomly from prescribed distributions. I then simulate this comparison for the empirical application. I discuss emergent patterns of these simulations and finish with concluding remarks and suggestions for future analyses.

Model

Here we consider a production unit whose technology and local parameters are fixed, captured by vector θ. The production function then has a fixed proportions relationship to the input and corresponding output, consistent with the findings of Berck and Hefland [18] and Paris [19]. The production unit if operated imposes a damaging externality, d, which is also generated proportionately to the input, also supported by studies developed by Hochman and Zilberman [15], Moffitt et al. [16], and Green and Sunding [17]. The nature of these fixed proportions relationships are captured by what are called "microparameter" or "putty-clay" models.

The production unit i decides whether to operate using the damaging input or not. If it chooses to operate with it, its decision is:

$$\max_{j,\ w_j} p_j \cdot y_j(w_j, \theta_i) - c(\theta_i) \cdot w_j - F_j(\theta_i) = \pi_i^w \tag{2.1}$$

where j is a good that may be produced by the unit, w_j is the input to produce it, p_j is the price of the good, y_j is the output, θ_i is unit i's specific local parameters, c is the per-unit cost of utilizing input w, and F_j is the fixed cost of production. From this, the unit chooses the most profitable good m it may produce with optimal, unconstrained input use w_m^*. I call this π_i^w, the profit-maximizing choice using input w, which has constant returns to scale.

If the production unit decides not to operate using input w, then it may produce another good, k:

$$\max_k p_k \cdot y_k(\theta_i) - F_k(\theta_i) = \pi_i^0 \tag{2.2}$$

from which it selects the profit-maximizing choice to produce good n with π_i^0 profits of constant returns to scale. Now the unit makes the profit-maximizing choice between producing good m with input w_m^* and good n:

$$\pi_i^* = A_i \cdot \max\left(p_m \cdot y_m(w_m^*, \theta_i) - c(\theta_i) \cdot w_m^* - F_m(\theta_i),\ p_n \cdot y_n(\theta_i) - F_n(\theta_i)\right) \tag{2.3}$$

$$\pi_i^* = A_i \cdot \max\left(\pi_i^w,\ \pi_i^0\right) \tag{2.4}$$

where π_i^* is the unit's total profits, scaled by its operation size, A_i. If $\pi_i^w - \pi_i^0 > 0$, the unit will choose to produce with the damaging input. If $\pi_i^w - \pi_i^0 \leq 0$, the unit will choose to produce without it. For simplicity, I call this difference the profitability of the damaging input, or the damaging input's marginal value, π^ν:

$$\pi_i^\nu = \pi_i^w - \pi_i^0 \tag{2.5}$$

Any unit causes an externality such that:

$$d_i = A_i \cdot \gamma_i \cdot w_i \tag{2.6}$$

$$D = \sum_i d_i \tag{2.7}$$

where d_i is unit i's externality, γ_i is a transfer function that relates unit i's production processes to its resulting externalities, and D is the total externality caused by the industry. Notice that a unit operating without w_i will not cause an externality. Notice also that a unit's externality is linear in its input use and size. While γ is a fixed factor for each unit, and therefore the externality is linear in γ, the transfer function γ itself is not necessarily linearly related to production processes.

The regulator decides to limit the total externality D first by setting an upper limit, $\bar{A}$, on the total size of externality-causing production such that:

$$\sum_i (A_i \mid w_i > 0) = \bar{A}. \tag{2.8}$$

In other words, the regulator can observe the use of the damaging input and only permits some units to use it, therefore restricting entry by others into the industry. At the time of the regulator's decision to place the upper limit $\bar{A}$, I assume: all units who wished to use the input could; all units that use the input made a larger profit relative to production without it; those that did not use the input made a larger relative profit through other activities; in the future, some units restricted from using the input would make a larger profit compared to their current production activity without it. Relative changes in prices or technology could alter this in the future, driving interest in entry into the industry.

For now, consider only the units who use input w. The regulator has restricted other units from entering the industry and contributing to the externality, but the regulator decides to reduce the total externality D. The regulator can do so in a variety of ways, each with different individual and aggregate outcomes. The first-best solution is a tax, τ, on the true marginal externality:

$$\tau \cdot \gamma_i \cdot w_i \quad \forall_i. \tag{2.9}$$

But because of limitations to monitor a unit's externality d, its input use w, or even its output y directly, a tax on any of these is impracticable. Instead, the first-best solution is a tax on the expected marginal externality, $\gamma \cdot \mathbb{E}[w]$, where $\mathbb{E}[w]$ is the expectation of input use.

$$\tau \cdot \gamma_i \cdot \mathbb{E}[w] \quad \forall_i \tag{2.10}$$

Therefore, the survival region, or the area in which firms remain in production, is:

$$\pi_i^w - \tau \cdot \gamma_i \cdot \mathbb{E}[w] \geq \pi_i^0 \tag{2.11}$$

$$\pi_i^\nu - \tau \cdot \gamma_i \cdot \mathbb{E}[w] \geq 0 \tag{2.12}$$

which corresponds graphically to the region OFBC in Figure 1. The units in area OAF will find it unprofitable under this tax to use the damaging input. From Figure 1, this tax as it becomes more restrictive will pivot about the origin. Essentially, units with a higher ratio of expected marginal externality to profitability than the tax rate will choose to exit the damaging industry, while firms with ratios lower than the tax rate will continue operating.

If there is little variability in input use, then the tax on the expected marginal externality should generate most of the gains that a tax on the true marginal externality would, with full information about input use. If however the variability in input use is large, the uncertainty will lead to significant inefficiencies. To explore how uncertainty propagates in the expected marginal externality tax, I will compare it directly with the tax on the true marginal externality. Notice that a tax on the true marginal externality could lead to adjustments on the intensive margin, as a unit has an incentive to reduce input use in the case of a true marginal externality tax. This is not so with a tax on the expected marginal externality since input use is unobserved and the unit's transfer function, γ, is fixed. To make this comparison, I assume that producing units cannot respond to taxation by adjusting input use per unit of output (i.e., units cannot adjust production on the intensive margin). Recall the assumption that there exists a fixed proportions relationship between input and output in microparameter models such as the one developed here, which is supported by the literature [15], [16], [17], [18], [19]. If this assumption holds, then a tax on the true marginal externality has a similar survival region to that of the expected marginal externality, except that input use is also taxed rather than the expectation of it:

$$\pi_i^{\nu} - \tau \cdot \gamma_i \cdot w^* \geq 0. \tag{2.13}$$

Let's return to the case where there is uncertainty regarding input use or output. The regulator can use two other policies: a cap on the transfer function (equivalently, a cap on the expected marginal externality), which I call "zoning", or a tax on the size of the unit, which I call a "land tax". Under a zoning policy, only units with:

$$\gamma_i \leq \Gamma \tag{2.14}$$

may operate, where Γ is the upper limit on the transfer function (equivalently, the upper limit on the expected marginal externality is $\Gamma \cdot \mathbb{E}[w]$). Graphically, the units in region DABG on Figure 1 will be pushed out of production, while those in ODGC will continue doing so. Under the land tax, a unit is charged a tax λ on the basis of its production size so that the survival region is:

$$\pi_i^{\nu} - \lambda \geq 0 \tag{2.15}$$

corresponding graphically to units in area HEBC in Figure 1, pushing out of production those in area OAEH.

Zoning, unlike the tax on the marginal externality, completely ignores a unit's profitability. It only considers a unit's marginal externality, having potentially very costly repercussions. The land tax, on the other hand, is blind to the marginal externality, and pushes out the least profitable units regardless of their damage, potentially having little effect on reducing the externality. These results depend on the joint distribution of the marginal externality and the profitability of the units. With a strongly negative correlation between the marginal externality and the profitability, the zoning, land tax, and marginal externality tax behave very similarly, as the most damaging units are also the least profitable. If a strongly positive correlation exists, the policies behave quite differently: zoning (the land tax) removes the most (least) damaging and most (least) profitable units so that the largest (smallest) reductions in the externality happen at the earliest stages of abatement, as well as the largest (smallest) costs. To achieve increasing levels of abatement, zoning (the land tax) must remove increasingly more (fewer) production units, since the remaining units have a decreasing (increasing) effect on the externality. The tax on the marginal externality, for a strongly positive correlation, has nearly no preference for which units to remove in which order; all have the same or similar marginal externalities per unit profitability. These relationships are an elaboration and extension of the insights gained by Green and Sunding [17], a summary of which is provided in Table 1.

The aforementioned policies are somewhat similar to those previously studied in the microparameter literature, except that past work has focused on policies requiring information that is not easily observable: pollution, input, and output [15], [16], [17]. The policies examined here instead reflect values that are observable in practice.

Also notice that in this analysis I assume a linear damage function exists, and so the cost of the policy is simply the sum in foregone profits by the production units. If instead there existed a convex damage function, a regulator would prefer instruments that more rapidly targeted the externality; in particular, the zoning policy. The additional costs that may be incurred could be outweighed by the benefits of abatement.

Now let us consider the case where reallocation is allowed between units, giving rise to a new set of policies. There is a subset of units who use the damaging input, and some that do not but would like to. In other words, the restriction $\bar{A}$ is binding. If this condition is met, and if the profitability of using the damaging input is larger for a non-damaging unit than for a currently damaging unit, the units will benefit from reallocation; this corresponds to a tradable permit system.

I consider three types of trading schemes: one without trading ratios (one-to-one trading), one with trading ratios (bidirectional trading), and one with asymmetrical trading ratios (unidirectional trading).

With one-to-one trading, unit b without the right to use the damaging input wishes to purchase the right if its profitability of using the input is larger than that of unit s with the right. Mathematically, units b and s are interested in trading if:

$$\pi_b^\nu > \pi_s^\nu. \tag{2.16}$$

Assuming that the limiting factor of expansion and reduction is operating size, these units trade up to b's ability to expand its damaging operations or s's ability to reduce its operations, so that they trade:

$$\min\left(A_b, A_s\right). \tag{2.17}$$

Under the one-to-one trading scheme, the total scale of the damaging industry ($\sum(A_i \mid w_i > 0)$) stays the same but the change in the externality is uncertain. If on average, buyers cause higher (lower) damage than sellers, the total expected externality ($\sum(A_i \cdot \gamma_i \cdot \mathbb{E}[w] \mid w_i > 0)$) will increase (decrease).

The ratio, or bidirectional, trading scheme also takes into consideration the trading units' transfer functions. This scheme aims to keep the externality exactly where it currently is by adjusting the scale of the production proportionately to the change in its expected marginal externality. In this case, buyer b is interested in purchasing the right to pollute from seller s if:

$$\frac{\pi_b^\nu}{\gamma_b} > \frac{\pi_s^\nu}{\gamma_s} \tag{2.18}$$

and the parties are again limited by their ability to expand or reduce their operations, weighted by their transfer functions:

$$\min\left(A_b \cdot \gamma_b, A_s \cdot \gamma_s\right). \tag{2.19}$$

In this trading scheme, the scale of the industry ($\sum(A_i \mid w_i > 0)$) goes up (down) if the buyers have smaller (larger) transfer functions than the sellers, but the total expected externality ($\sum(A_i \cdot \gamma_i \cdot \mathbb{E}[w] \mid w_i > 0)$) is designed to stay the same.

The unidirectional trading scheme is a blend of one-to-one trading and bidirectional trading with the intent of hedging against uncertainty of variability in the damaging input. If the buyer has a larger (smaller) transfer function than the seller, the transaction is treated as ratio (one-to-one) trading. In this scheme, the scale of the industry cannot increase as in bidirectional trading, nor can the total expected externality increase as in one-to-one trading. With any trade, the scale either stays the same and the expectation of the externality decreases or the scale decreases and the expectation of the externality stays the same. Units b and s will be interested in trading if:

$$\begin{cases} \pi_b^\nu > \pi_s^\nu, & \text{if } \gamma_b \leq \gamma_s \\ \frac{\pi_b^\nu}{\gamma_b} > \frac{\pi_s^\nu}{\gamma_s}, & \text{otherwise.} \end{cases} \tag{2.20}$$

The parties will be subject to the scaling constraints again according to the relative magnitudes of their transfer functions, given by:

$$\begin{cases} \min\left(A_b, A_s\right), & \text{if } \gamma_b \leq \gamma_s \\ \min\left(A_b \cdot \gamma_b, A_s \cdot \gamma_s\right), & \text{otherwise.} \end{cases} \tag{2.21}$$

Unidirectional trading may behave more like one-to-one trading or more like bidirectional trading depending on the joint distributions of γ and π^ν. If a negative correlation exists, unidirectional trading should behave more like one-to-one trading; the right to use the damaging input is moving from sellers with high expected damage to buyers with low expected damage, resulting in a one-to-one transaction. If a positive correlation exists, unidirectional trading behaves more similarly to bidirectional trading, with permits moving from sellers with low expected damage to buyers with high expected damage, resulting in a discounted trade.

Empirical Application

The Platte River Basin flows from west to east, extending through the states of Wyoming, Colorado, and Nebraska. The Platte River serves as critical habitat to one endangered and three threatened species listed under the Federal Endangered Species Act [20]. In an effort to restore habitat, the three states are participating in a cooperative agreement to reduce water usage. In this application, I focus on one particular jurisdiction within the Basin: the Twin Platte Natural Resources District (Twin Platte NRD or "the District"), located in western Nebraska. For a map of the District, see Figure 2.

The Twin Platte NRD is one of 23 Natural Resources Districts (NRDs) in Nebraska. Local NRDs are governmental authorities charged by the State of Nebraska with the responsibility of managing its soils and water. NRDs have the authority to regulate the extraction and use of groundwater: they can set a well moratorium, cap and certify irrigated acres, and levy taxes. Importantly, NRDs have the authority to enact any of the policies analyzed here; the regulatory framework of the Twin Platte NRD in particular conforms to the model setup.

The Twin Platte NRD encompasses four counties that overlay the Ogallala Aquifer, an unconfined aquifer that is hydrologically connected to the Platte River. Groundwater is an abundant and valuable resource for the region, whose economy is driven by irrigated agriculture. Surface water and groundwater irrigate approximately 325,000 acres of farmland in the District [21].

Intensive groundwater pumping has led to decreased surface water flows in the Platte River. The District, with its authority to regulate groundwater, has undertaken a number of actions to curb water usage and supplement surface water flows. The District placed a moratorium on the drilling of wells in 2004, capped and certified irrigated acres in 2004, and implemented in 2005 a unidirectional trading scheme for certified irrigated acres. More recently, the District in 2013 began the construction of a stream augmentation project and in 2014 levied an “occupation tax”, or land tax, on irrigated acres.

The Twin Platte NRD is interested in reducing stream depletion while providing flexibility to its agricultural producers. As such, the District does not meter or set allocations of groundwater extraction. In 2005, the District implemented a trading scheme of irrigated land, which considers the expected marginal damage and land size, and has had almost 200 transactions to date (see Table 2). The nature of these regulations makes an interesting case study for this work, and illustrates this work’s policy relevance.

Data Description

I make use of primary and derived section-level hydrologic, agronomic, and economic data in the Twin Platte NRD. I do so by employing a number of publicly available data sources and decision-making tools. I find the profitability of irrigation for each section, which depends on local parameters such as climate, soil type, variable cost of groundwater pumping, and well yield, the rate at which a well can pump water. Then I use relationships between groundwater and surface water interactions to find the marginal externality of groundwater pumping on surface water flows, called the stream depletion factor. Summary statistics of these properties are available in Table 3. Notice the wide range of variability in the marginal value of irrigation and the stream depletion factor, but the small variability in irrigation application. Graphical representations of these properties can be found in Figures 3 and 4.

Marginal Value

Economic Data

To obtain each section's marginal value of irrigation, I derive the difference between its profit-maximizing irrigated and dryland profits per acre. I find these values by using the 2010 single-year, single-field version of *Water Optimizer*, an agricultural decision support tool that predicts the profit-maximizing strategy based on field-level characteristics [22]. Using data from the United States Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS), I allow producers to choose between the four predominant crops grown in the region in the 10-year period from 2003 to 2012, which are alfalfa, corn, sorghum, and wheat [23].

I use all input and output prices, such as commodity prices, and fixed and variable costs of production, given in *Water Optimizer*, which their developers obtained through sources such as NASS, the Nebraska Energy Office, and the Chicago Board of Trade [22].

Well Data

To obtain the variable costs of pumping, I assume that all producers have center pivot irrigation, powered by electricity with pumping efficiency of 90 percent. The Nebraska Department of Natural Resources has publicly available well records that include well yield and depth to water [24], also crucial components to the cost of pumping. I specifically use a subset of these well records, looking at active wells used for irrigation, and interpolate well yield and depth to water at the centroid of each section.

Agronomic Data

Water Optimizer embeds climate characteristics by looking at long-term average conditions in each county. Based on field-level studies, it provides the maximum irrigated and dryland yields and the maximum irrigation application by county. I pinpoint these values to the county centroids, and then interpolate to the section level.

Physical Data

Soil types greatly affect the quality of the land, as well as the soil's ability to retain water. As an example, fine soils that have small pore space better retain applied irrigation water in the root zone of the crop compared to coarse soils. The implication of this is that producers with coarse soils often must apply more irrigation water to meet the crop requirement. As such, one of the key inputs to *Water Optimizer* is the land's soil type. Using the National Resource Conservation Service's soil survey, STATSGO, I find the predominant soil type of each section.

Much of the land in the Twin Platte NRD is hilly and unsuitable for irrigated agriculture, as it causes erosion and is difficult to operate machinery. Instead, sloping lands are used primarily as rangeland; the District also restricts lands with a 10 percent grade from acquiring certified irrigated acres to limit soil erosion. I find that removing these sections is important for the analysis; otherwise, the simulation results in irrigated land moving to areas that are not realistically suitable for irrigation. Therefore, I use elevation data to find the slopes within each section, and then remove sections that contain a slope of 10 percent or more[1]. A visualization of the existing certified irrigated acres and the sections of land remaining in the analysis can be found in Figure 2.

Marginal Externality

To quantify the depleting effect of groundwater pumping on surface water flows, the Twin Platte NRD has partnered with other districts in the Nebraskan portion of the Platte River Basin. To assist in policy analysis, the districts developed a joint surface water-groundwater model, called the Platte River Cooperative Hydrologic Study (COHYST). COHYST links a surface water model created using STELLA and a groundwater model created using the United States Geological Survey's MODFLOW.

[1]Of the 325,000 irrigated acres in the District, only about 78,000 irrigated acres overlap with the sections I include in the analysis. These fields that have 10 percent slopes may either be grandfathered into irrigation rights or contain a very small area of sloping land.

The model simulates the effects of seasonal, cyclical groundwater pumping over a 50-year period, calculating the proportion of pumped groundwater that reduces baseflow to the Platte River. This proportion is called a stream depletion factor (SDF), equivalent to the transfer function, and which takes on a number between 0 and 1. There is wide variability of section-level SDFs in the District, and those with the highest SDFs are typically closest to the streams. Figure 5 illustrates how this trait varies spatially.

Then, to obtain field-level irrigation application, I use the unconstrained and profit-maximizing values given by *Water Optimizer*. The product of irrigation application and the SDF will give the true marginal externality of each section.

Results

Using the microparameter model developed, I compare the aggregate reduction in industry profits under zoning, tax, and trading policies to regulate a spatially heterogeneous externality. I perform two types of analyses in this section. First, I generate synthetic data by randomly drawing from prescribed distributions of producing units' characteristics, allowing me to observe whether findings are robust or sensitive to specific relationships. I then apply the model to the case study of the Twin Platte NRD.

I assume that the regulator can obtain information on the transfer function and the size of a firm, but that a firm's profitability and input use are only known privately. A regulator could infer a firm's profitability by observing how it responds to increasing taxes on its firm size or transfer function, but input use would be much harder, if not impossible, to infer without additional resources. However, I do consider input use in calculating the reduction in the externality.

Simulation of Synthetic Data

In this simulation, I randomly draw from distributions of input use w, scale of production A, profitability π^{ν}, and transfer function γ for 1,000 producing units, half of which currently produce with the polluting input and the rest which do not. I assume that input use among units is normally distributed, with a mean of 0.5 and a standard deviation of 0.1. The remaining properties are uniformly distributed. All values are normalized between 0 and 1 and are sampled using Cholesky decomposition to achieve the desired covariances.

I induce correlations between firm properties, ranging from -1 and +1, to explore how relationships that may exist in the real world affect the relative performance of the policies considered. For example, if the profitability of the polluting activity is negatively correlated with the firm's marginal externality, then a policy that targets highly damaging firms should be quite cost-effective since firms with high marginal externalities also have lower profitability. In particular, I am interested in correlations between the profitability of the damaging activity π^{ν} and each of the two components of the true marginal externality, input use w and transfer function γ (equivalent to the expected marginal externality).

Correlation: Profitability and Input Use

In this scenario, I test correlations between firms' input use w and the profitability of the input π^{ν}. A negative (positive) correlation will mean that firms with higher profitability generally use less (more) of the damaging input. For these tests, the correlation between the profitability and the transfer function is zero.

As expected from the model, if the distribution of input use has little variation compared to that of the transfer function, differing correlations between profitability and input use have little effect on the relative performance of the policies. In some respect, this is a surprising and yet intuitive result: uncertainty in input use does not result in negative environmental or economic outcomes. Policies that do not directly meter input use w can still achieve most of the gains that one with perfect information would. This result is driven by the relatively smaller variability in input use w compared to that of the transfer function γ. This result does not hold if input use has comparatively similar or larger variability than the transfer function. This is an important empirical question for its application.

Correlation: Profitability and Transfer Function

Here I test the correlations between units' profitability π^{ν} of the damaging input and their transfer function γ. A negative (positive) correlation will mean that units with higher profitability have a lower (higher) transfer function. For these tests, the correlation between the profitability and the input use is zero.

Negative Correlation

A negative correlation between π^{ν} and γ means that units with low profitability have high marginal damage, and that producers with high profitability have low marginal damage. Recall from Table 1 that all tax and zoning policies, ones that target high-damaging, low-profitability, or a blend of these, are very cost effective at low abatement levels and very costly at high abatement levels. The tax and zoning policies retire approximately the same producing units in the same order when a strong negative correlation exists. As a result of the negative correlation, it is very cheap to achieve low abatement levels, but becomes increasingly expensive as the abatement level increases, the intuition behind the curvature in Figure 8. At the lowest levels of abatement, the least profitable and most damaging units are being retired; at the highest levels of abatement, the most profitable and least damaging units are being retired.

In the case of a negative correlation, reductions of industry size to achieve a given abatement level are also closer to being the same across tax and zoning policies (see Figure 6); this is a combined result of the policies targeting approximately the same producers in the same order and the policies achieving the same environmental and economic outcomes no matter the way in which the units are targeted.

As a result of this negative correlation, the relative cost-savings between alternative tax and zoning policies are small. This result is consistent with prior work, such as Babcock et al., which finds that negative correlations make simple, easily observable proxies good substitutes for spatially targeted policies [10].

Positive Correlation

A positive correlation means that units with higher marginal externalities are also the most productive. This is not an ideal case, as policies are very costly at lower abatement levels. As seen from Figure 9, the curvature of the policy cost becomes more linear under a positive correlation. In other words, the marginal costs to achieve any abatement level are nearly the same everywhere. The intuition behind this is that for approximately every unit increase in abatement, a similar unit cost is incurred under a positive correlation. Therefore, reduction in profitability becomes approximately linear with respect to abatement level under more positive relationships. If a perfectly linear and positive relationship exists between the profitability and the transfer function, then all tax and zoning policies behave almost identically in terms of the reductions in profitability to decrease the externality.

Yet, under positive correlations, the relationship between reductions of the externality and of industry size are quite different between policies, as illustrated in Figure 7. This is because the ordering of producers who are pushed out of production is different (see Table 1). The zoning policy and the land tax in fact have an almost completely opposite ranking to retire producers, whereas the tax on the transfer function is indifferent of the order, as every unit has approximately the same $\frac{\gamma}{\pi^{\nu}}$. For the land tax to achieve the same level of abatement as zoning, it must retire many more units since it targets low-productivity units first, which are also low-damaging in this case.

Tax and Zoning Policies

Looking at Figures 6 and 7 as examples, the zoning policy is very effective at reducing the externality per reduction in industry size across negative and positive correlations. Zoning is the only policy that ignores the unit's profitability, so that regardless of the relationship between π^{ν} and γ, the most damaging units will be retired first, keeping relatively many more units in production than that of other policies. The zoning policy almost always leaves in production the largest amount of total damaging units to achieve the same abatement compared to any other policy; the only exception being that when a strong negative correlation exists, zoning is outperformed by the bidirectional and unidirectional trading schemes (discussed below). Of the tax policies, the land tax is the least effective at reducing the externality with the reduction in industry size, as it is blind to contributing components of the externality. This is particularly true for positive correlations between π^{ν} and γ, as it retires first those units with low profitability and therefore low marginal damage. The land tax must retire many more units in order to achieve the same abatement level as the zoning policy.

Looking instead at the performance of policies in terms of reductions in profitability, as seen in Figures 8 and 9, zoning is very costly, and especially with highly positive correlations as anticipated in the model. Zoning in this case pushes out the most damaging and most productive units out of production in the beginning. For either a positive or negative correlation, there exists an interesting abatement level at which the land tax becomes more costly than the zoning policy. As abatement targets go up, the effectiveness of the zoning policy to achieve that target deteriorates quickly, as it takes more and more units, regardless of profitability, to retire. In other words, these units have progressively smaller and smaller effects on reducing the externality. The land tax, which ignores the transfer function, continues pushing out production units with high marginal damage, even at high abatement targets.

Of the tax policies, the most costly policy is zoning at low abatement levels and the land tax at high abatement levels. Importantly, across correlations, the tax on the transfer function achieves most of the gains that a tax with perfect information would achieve. These two taxes are the least costly of the tax and zoning policies at all levels of abatement and across correlations. See the overlap between the two policies in Figures 8 and 9.

Tradable Permit Systems

Allowing for entry into the economy, the introduction of trading programs presents large cost-savings opportunities that could not be realized by tax or zoning policies amongst existing users. New producers that have smaller transfer functions or larger profitability are able to replace those with higher transfer functions or who are less profitable. Especially in the case of a negative correlation, introducing any type of trade increases aggregate profitability. Bidirectional trading under any correlation is the first-best policy under imperfect information, as it allows for the expansion of industry size while maintaining the existing abatement level (see Figures 8 and 9).

Unidirectional and one-to-one trading in the case of a negative correlation lead to immediate reductions in the externality, without the need to reduce the size of the industry (see Figure 8). This is because buyers of permits are those who are more profitable and less damaging than the sellers of permits, leading to economic and environmental benefits immediately.

As expected in the model, unidirectional trading behaves most similarly to one-to-one trading when a negative correlation exists, and most like bidirectional trading when a positive correlation exists. Recall that unidirectional trading is a blend of the two trading schemes. When a negative correlation exists, buyers generally have lower marginal externalities than sellers; the program stipulates that such transfers be done at a one-to-one rate. When a positive correlation exists, the opposite is true: buyers have a higher transfer function than sellers and must discount their transaction proportionately, as done in bidirectional trading.

There is one exception when a trading program can cause large, unexpected damages. The one-to-one trading scheme in the presence of a positive correlation can lead to an increase in the externality, as the buyers are those with high transfer functions and the sellers are those with low transfer functions (see Figure 9). Because this trading scheme ignores the relative differences between the buyer's and seller's transfer functions, and simply exchanges at a one-to-one rate, aggregate damage will increase under a positive correlation. Notice in Figure 7 that in order to maintain the initial abatement level, approximately two-fifths of the industry size must be reduced under one-to-one trading.

Like the tax and zoning policies, the trading programs have increasingly linear effects of total costs with abatement level as the correlation becomes more positive, for the same reason stated earlier. Still, their benefits of increasing profitability relative to the other policies is substantial and fairly robust across correlations. Bidirectional trading is always most cost-effective of all policies at decreasing the externality. Interestingly, the magnitude of cost-savings between this first-best solution and its alternatives are much larger under negative correlations than under positive correlations, a result that is different than that found in the existing literature. This finding is driven by allowing entry into the industry, whereas prior work did not.

Interesting relationships between industry size and abatement also emerge: consistently, bidirectional trading has a linear relationship, achieving a fixed quantity of abatement per reduction in industry size. In fact, this is actually a defining feature of the bidirectional policy, as it neither abates more or less than expected at a particular industry size, unlike any other policy. From a regulatory perspective, this is a nice feature of bidirectional trading in that in order to reduce damage by a certain proportion it is clear that a reduction in industry size by that same proportion is necessary. Under a negative correlation, all other policies outperform bidirectional trading with respect to industry size, but the relationship is nonlinear. See Figure 6 for the graphical illustration.

Simulation of Empirical Data

The properties of irrigated and dryland producers in the Twin Platte NRD are mapped in Figure 3. Notice the wide range of variability in their transfer functions, which is the SDF, and little to no correlation with the profitability of irrigation. Also notice the sizable overlap between the profitability of irrigated and dryland fields; this indicates interest in entry into the industry of irrigated agriculture.

In the case of stream depletion, the expected marginal externality or transfer tax is equivalent to the tax on the SDF and the tax on the true marginal externality is equivalent to a tax on stream depletion. The SDF tax and the zoning policy perform very similarly to the tax on stream depletion (see Figure 10), indicating that the predominant driver of stream depletion in the Twin Platte NRD is the SDF, not water use. The land tax at all levels of abatement is the least cost-effective to increase streamflow in the Platte River. One-to-one and unidirectional trading behave quite similarly to one another, meaning that buyers of irrigated land have smaller SDFs than the sellers. Additionally, one-to-one and unidirectional trading are more cost-effective than the tax on stream depletion to about 18,000 and 24,000 acre-feet of increased streamflow, respectively (see Figure 10). For perspective, the Twin Platte NRD is looking to reduce stream depletion by 7,700 acre-feet. Bidirectional trading is by far the most cost-effective policy, as irrigated acres expand in the regions that have the lowest SDFs. To achieve the increased streamflow target of 7,700 acre-feet, a bidirectional trading scheme would actually increase profitability in the District by an estimated $35 million.

Interestingly, unidirectional trading has a fairly linear relationship between streamflow enhancements and retired irrigated land permits, a defining characteristic of bidirectional trading (see Figure 11). Unidirectional trading also has the unique ability in this case to increase streamflow significantly while maintaining the same quantity of irrigated land. Zoning, the SDF tax, and the depletion tax keep the most amount of irrigated land in production at almost every level of reduction, as they push out the most damaging lands first.

Conclusions

Spatially heterogeneous externalities are abundant in the real-world, but the ability to monitor the polluting inputs or resulting damage is not. Consequently, management strategies in practice have effects on firms' production at the external margin. In this paper, I present and analyze alternative policies that can be implemented with more readily observable properties, using a microparameter framework to capture the discrete nature of firm characteristics and regulatory action.

I find that regardless of the correlation between input use and profitability, the differences in aggregate abatement, costs, and industry size are negligible. The ranking of policies also goes unchanged across correlations. Comparing the performances of a true marginal externality tax and a transfer function tax, the welfare loss of imperfect monitoring is small, a result that is surprising and debunks concerns regarding imperfect monitoring of input use. This result is driven by the assumption that the transfer function has much larger variability than input use, one that is substantiated by the empirical evidence of the application studied here. This has important and interesting implications for other nonpoint source pollution problems, where loading rates or input use may be inconsequential compared to other firm characteristics, such as its distance to the region of concern.

This work also illustrates the importance of the correlation between a firm's transfer function and marginal value of the damaging input. The magnitude of cost-savings between alternative policies depends critically on this relationship: under a negative correlation, alternative tax policies on existing users have little differences in welfare loss, while under a positive correlation, the differences are large. Interestingly though, it is under a negative correlation that the cost-savings of allowing entry through tradable permit systems are most stark.

Allowing entry through any tradable permit system achieves economic gains not possible through tax and zoning instruments at reasonable reductions in the externality. However, one-to-one trading can result in negative and unexpected damages in some cases.

The Twin Platte NRD currently has a unidirectional policy and would be able to achieve their goals for streamflow enhancements, but at significant loss in profit compared to the bidirectional trading scheme. Still, many more transactions would have to occur in order for this streamflow target to be realized. I assumed frictionless trading in my model, but it may be the case that high transaction costs are impeding trade.

The simulation of the Twin Platte NRD illustrates the importance of local factors that drive cost-effectiveness. At low levels of abatement, the tax and zoning instruments behave very similarly while trading policies provide the opportunity for additional economic and environmental gains. This is especially true for the bidirectional trading scheme. Unlike Kuwayama and Brozović's findings, this spatially differentiated scheme is not approximated by one-to-one trading at low abatement levels. This may be driven by the primary distinction between the two studies: Kuwayama and Brozović's model allows for continuous regulations, a reflection of the policies in the Republican River Basin [13], while this work looks at regulations that operate on the extensive margin, a reflection of the policies in the Platte River Basin. Interestingly, the Republican and the Platte River Basins neighbor one another and yet are drastically different in terms of their policy options. The importance of understanding local institutions and implementing tailored solutions to match the environmental and societal problems cannot be overstated.

While I compared the aggregate reduction in profits to achieve increasing abatement levels, I have not yet performed firm-level welfare analyses. These would provide important insights about the distribution of losses and equity of the policy instruments. Further, from an analytical perspective, allowing entry and exit is also possible by removing the binding cap on the industry size and implementing a tax, the first-best of which would be the transfer tax. To complement the work done here, I will conduct these analyses as next steps.

In order to compare a tax with perfect information to its closest substitutes, I made the assumption that firms do not make intensive adjustments of input use, which may be the case for some industries but not all. Much theoretical work shows that firms, responding to regulations on input use, will make intensive adjustments. Future work could explore in which industries and under circumstances policies that enable intensive adjustments lead to significant welfare gains. Of course, this requires monitoring and such an analysis should consider its cost. Therefore, while this model has allowed me to draw conclusions regarding imperfect monitoring, I cannot draw any regarding the welfare loss of regulations that affect intensive rather than extensive adjustments. Work that analyzed these differences would add to the literature on the value of information.

Tables and Figures

Table 1: Comparison of Policy Instruments by Correlation Between γ and π^{ν}

The abatement relationship $\frac{\partial}{-(\partial \bar{A})}$ relates how, as each of the policies becomes more restrictive, the properties of the producing units it affects change. As an example, as the land tax τ is raised, the industry size $\bar{A}$ is shrinking and the profitability of units π^{ν} it affects is increasing.

Correlation	Abatement Relationship	Transfer Function Tax	Zoning	Land Tax
$+1$	$\frac{\partial \gamma}{-(\partial \bar{A})}$	$= 0$	< 0	> 0
	$\frac{\partial \pi^{\nu}}{-(\partial \bar{A})}$	$= 0$	< 0	> 0
-1	$\frac{\partial \gamma}{-(\partial \bar{A})}$	< 0	< 0	< 0
	$\frac{\partial \pi^{\nu}}{-(\partial \bar{A})}$	> 0	> 0	> 0

Table 2: Summary of Transfers in the Twin Platte NRD

Year	Transfers
2005	4
2006	0
2007	1
2008	9
2009	29
2010	26
2011	32
2012	40
2013	33
2014	9
Total through February 2014	183

Table 3: Descriptive Statistics: Section-Level Values in the Twin Platte NRD

Variable (n = 1450)	Mean	Std. Dev.	Minimum	Maximum
Irrigated profits per acre, $/ac	391.50	32.26	183.47	459.98
Dryland profits per acre, $/ac	124.97	46.17	0	219.79
Marginal value of irrigation, $/ac	266.53	38.21	53.69	384.45
Total available land area, ac	639.17	16.19	555.62	745.60
Maximum irrigated land area, ac	540.52	87.14	0	714.87
Existing irrigated acres, ac	53.68	134.249	0	614.8475
Existing dryland acres, ac	585.49	134.60	11.18	744.58
Irrigation application, ac-in/ac	14.89	1.32	7.05	29.23
Stream depletion factor, %	48.97	29.29	1	98
Stream depletion per acre, ac-in/ac	7.25	4.38	0	15.55

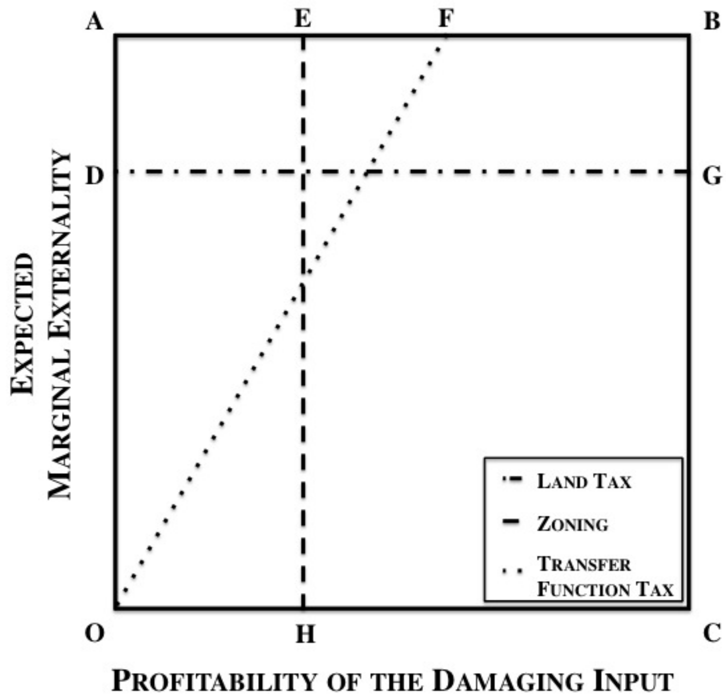

Figure 1: Graphical Illustration of Microparameter Policies
(1) A land tax is a flat tax based on the size of the producing unit, affecting the least profitable units first. Under a land tax, units in OAEH no longer find it profitable to use the polluting input while units in HEBC continue producing. (2) Zoning sets a cap on the expected marginal externality of producing units so that any unit above this cap may not operate. The units in DABG are removed and the units in ODGC may continue operating. (3) The transfer function tax (or the expected marginal externality) makes it unprofitable for units with a high ratio of expected marginal externality to profitability. In the triangle OAF, units will not produce under the transfer function tax. In the space OFBC, units will continue operating.

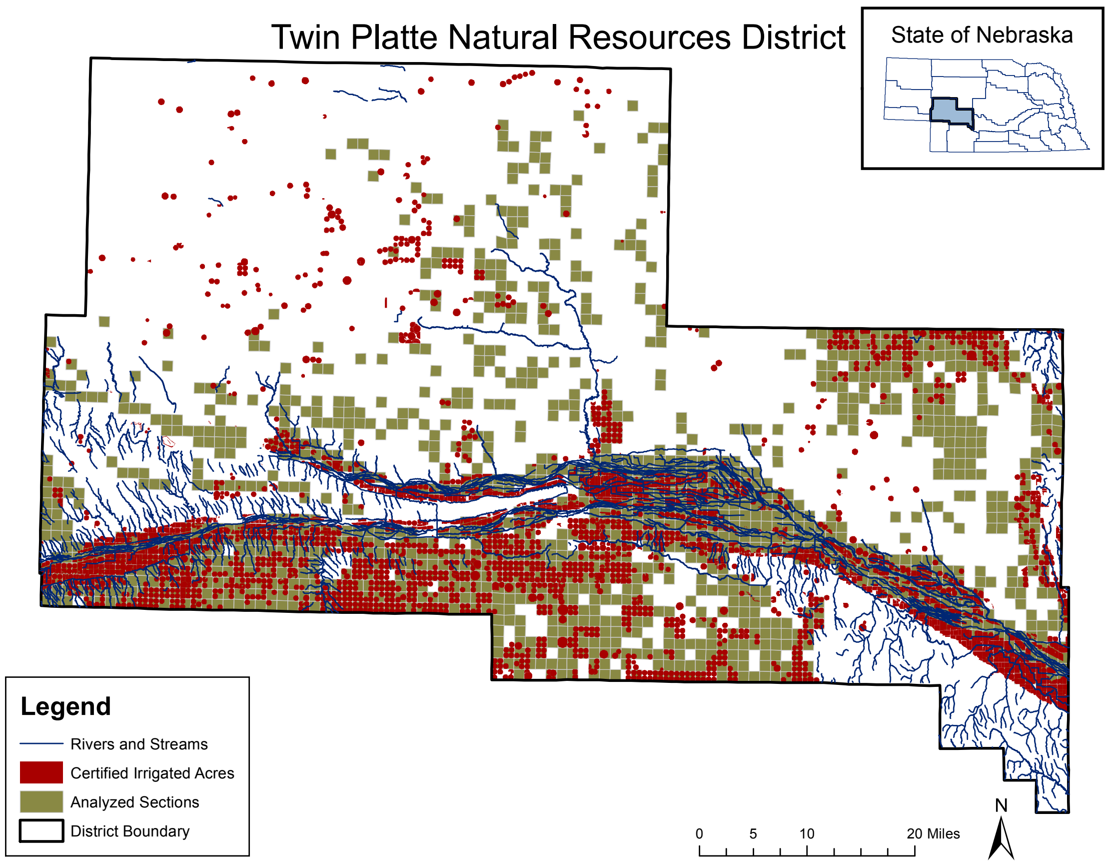

Figure 2: Twin Platte NRD: Study Area
The above map shows the District's location within Nebraska, its boundary, and the stream network. Also depicted are the existing certified irrigated acres in the District, totaling approximately 350,000 acres, and the sections that I analyze in this work, having slopes of less than 10 percent.

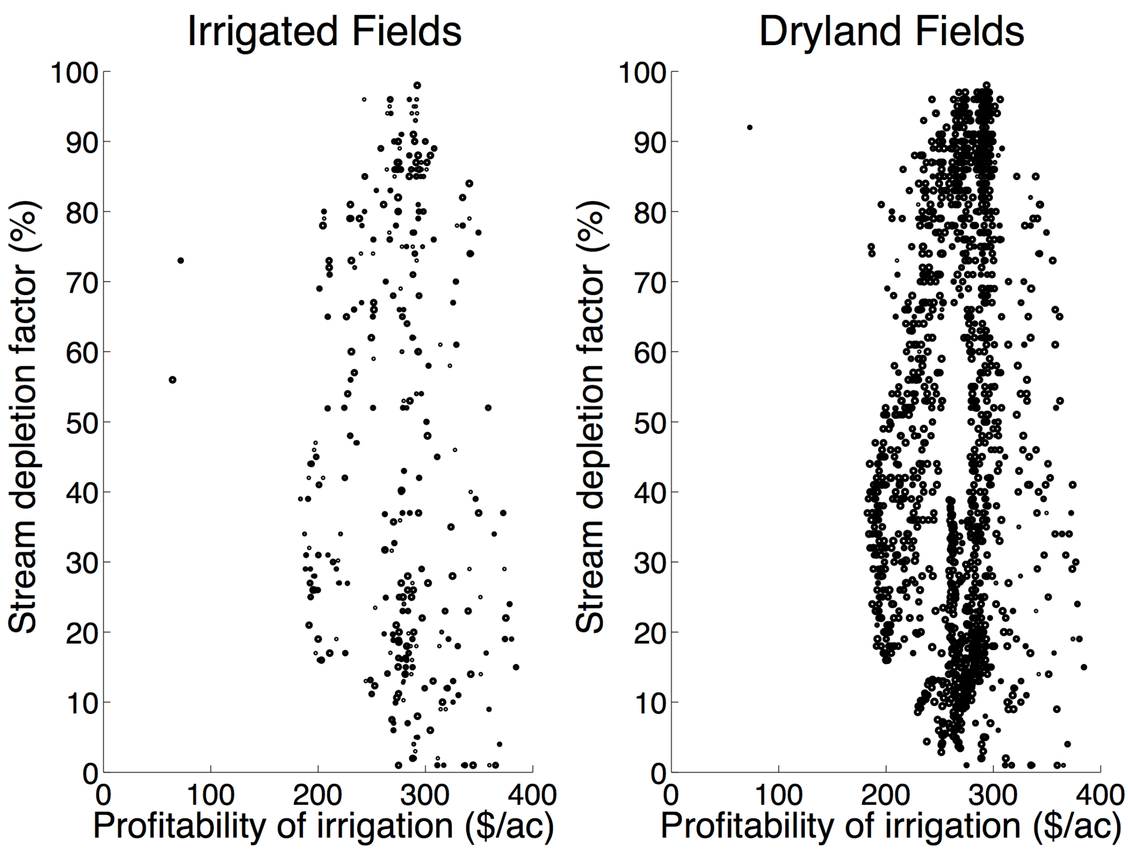

Figure 3: Twin Platte NRD: Producer Properties
The figure depicts irrigated fields on the left and dryland fields on the right. Their marginal value of irrigation is along the horizontal axis and their transfer functions, the stream depletion factors, of irrigation along the vertical axis. The points are weighted by field size.

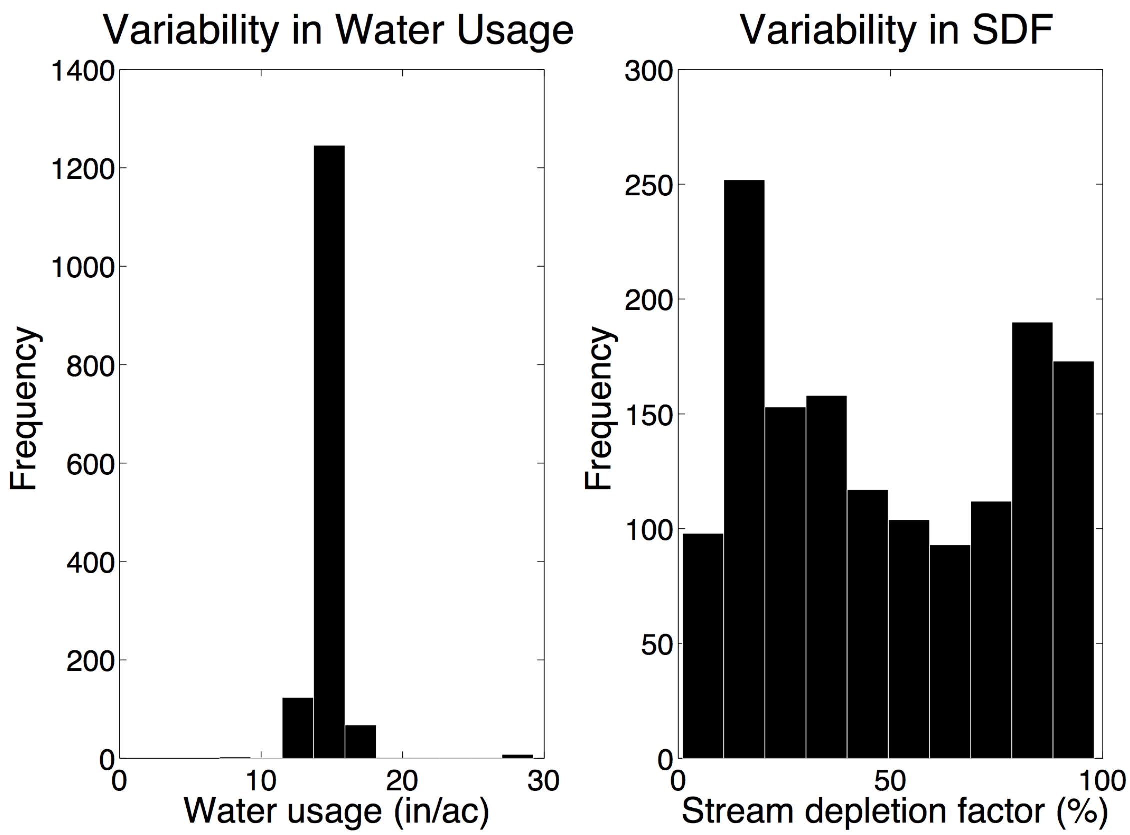

Figure 4: Twin Platte NRD: Variability of Irrigation Application and Transfer Function
The profit-maximizing irrigation application is relatively uniform across the District, but there is high variability in the stream depletion factor.

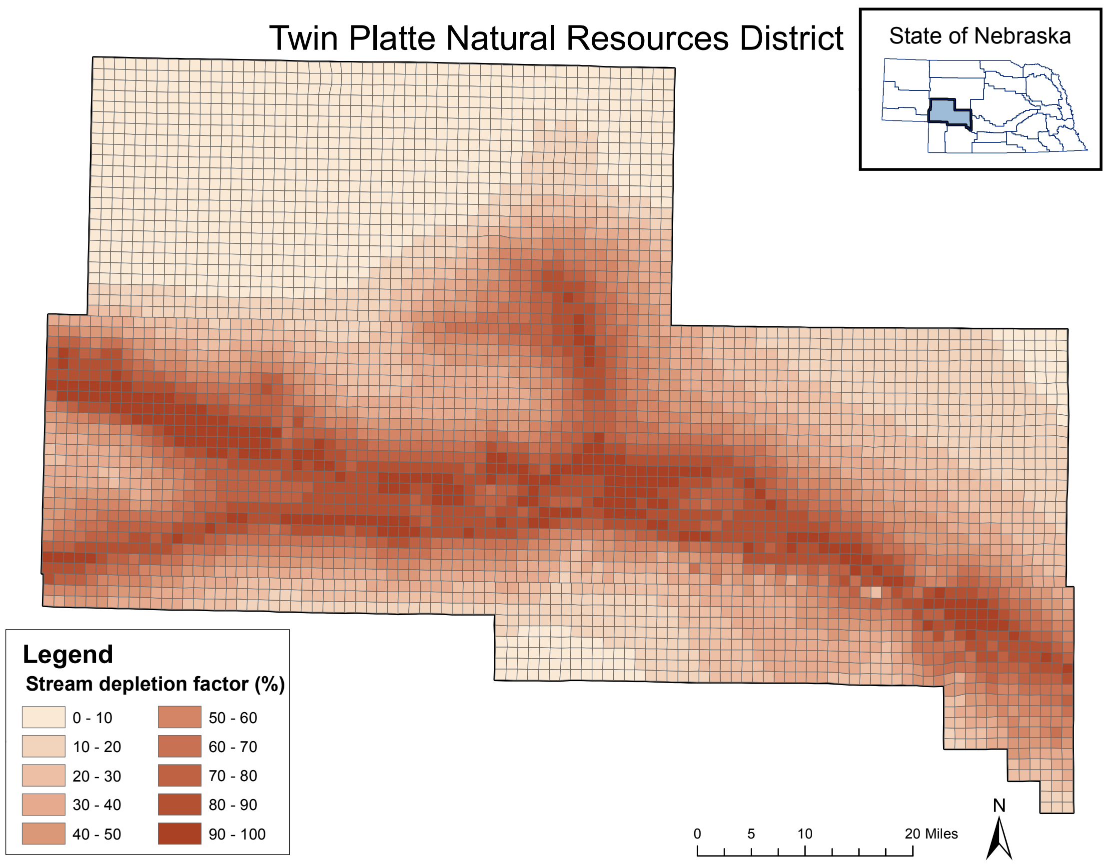

Figure 5: Twin Platte NRD: Spatial Heterogeneity
The spatial heterogeneity of the transfer function varies from 0 to 100 percent in the District, largely dependent on the closeness of the section to the stream network.

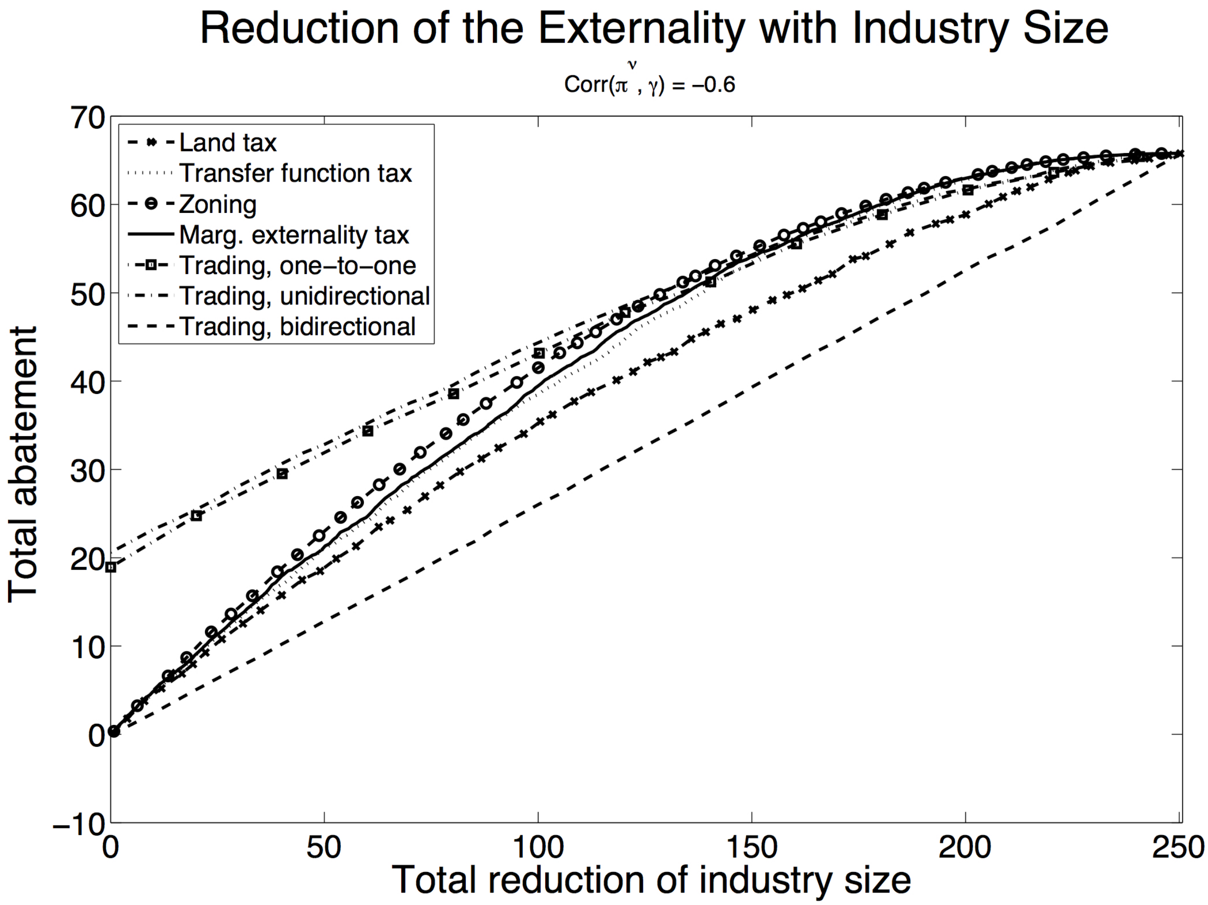

Figure 6: Reductions of the Externality with Reductions in Industry Size for a Strong, Negative Correlation Between π^{ν} and γ

One-to-one and bidirectional trading result in the largest industry size for the same abatement levels for nearly 50% of the possible abatement. The tax and zoning policies behave similarly to one another as they retire approximately the same producing units in the same order. The bidirectional trading scheme is linear by design, only abating with retirements in industry size.

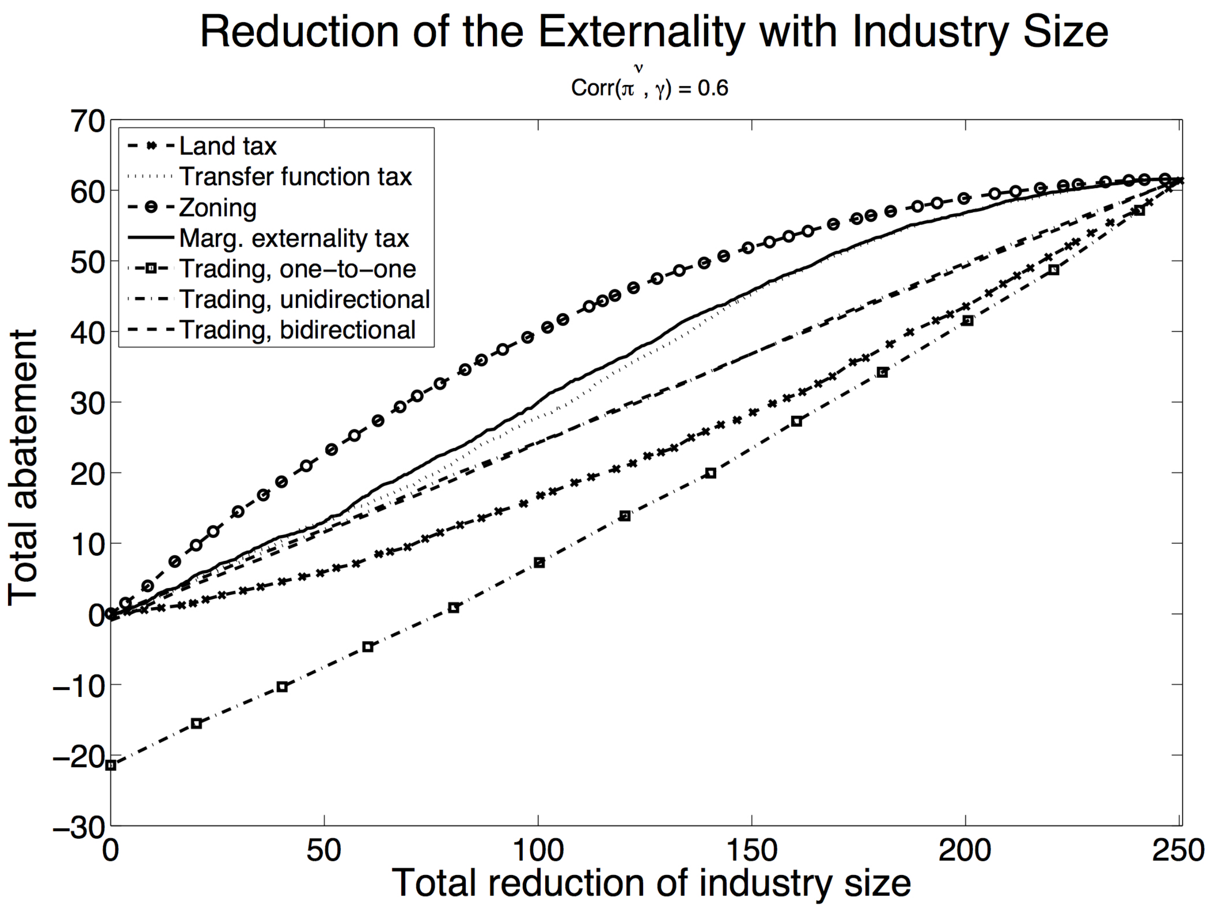

Figure 7: Reductions of the Externality with Reductions in Industry Size for a Strong, Positive Correlation Between π^ν and γ

One-to-one trading, which performed especially well under a negative correlation, performs poorly under a positive correlation. Zoning and the bidirectional trading have the same relationships that they did under negative correlations. In this case, unidirectional trading is similar to bidirectional trading. The land tax is highly inefficient under positive correlations.

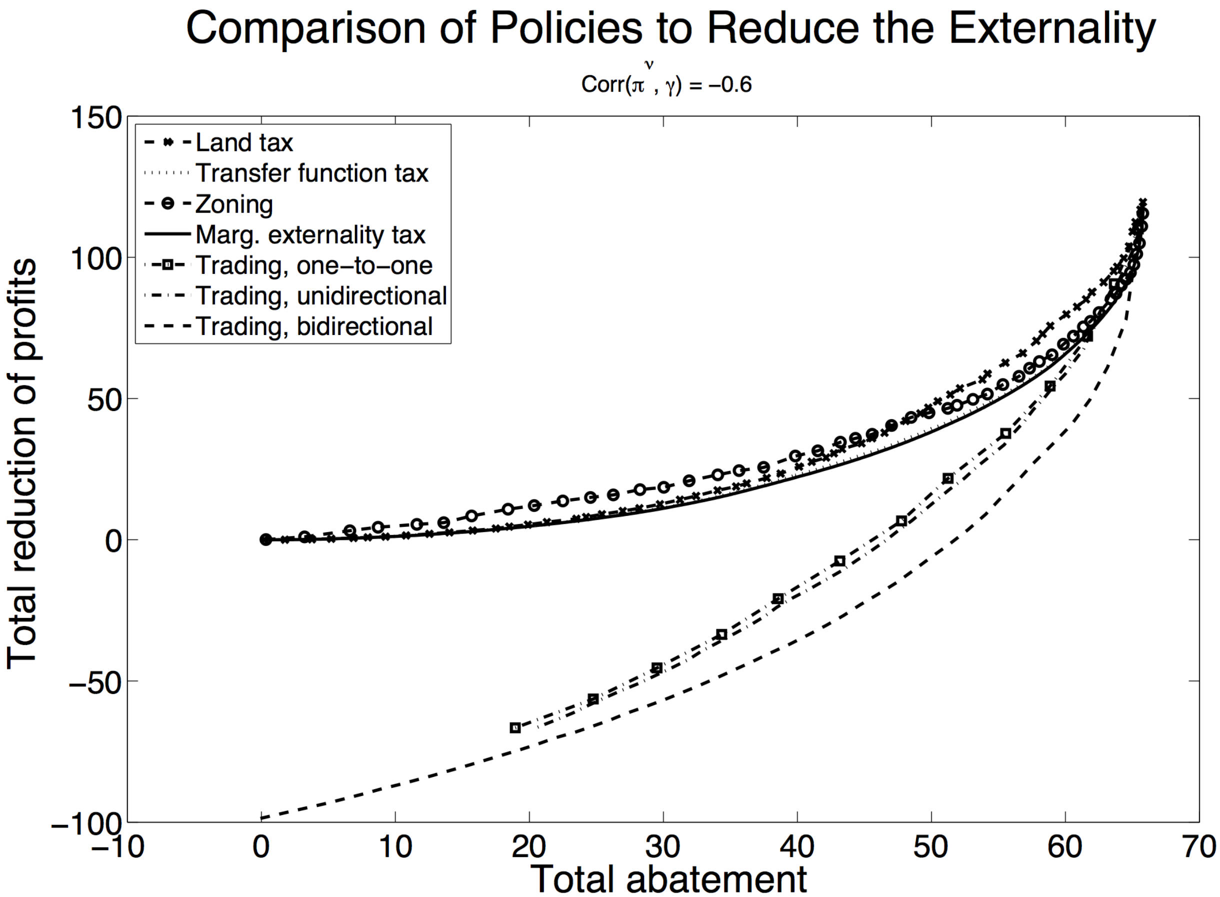

Figure 8: Comparison of Alternative Policies Under a Strong, Negative Correlation Between π^{ν} and γ

Notice the curvature of the policies, which indicates at lower levels of abatement, it is very cost-effective to decrease the externality. Notice also that the tax and zoning polices perform very similarly to one another, with negligible differences in total costs. Trading schemes offer environmental and economic gains not possible through tax instruments. For the case of a negative correlation, unidirectional trading approximates one-to-one trading, as buyers have lower expected marginal externalities than sellers, resulting in a one-to-one trading ratio under the unidirectional scheme.

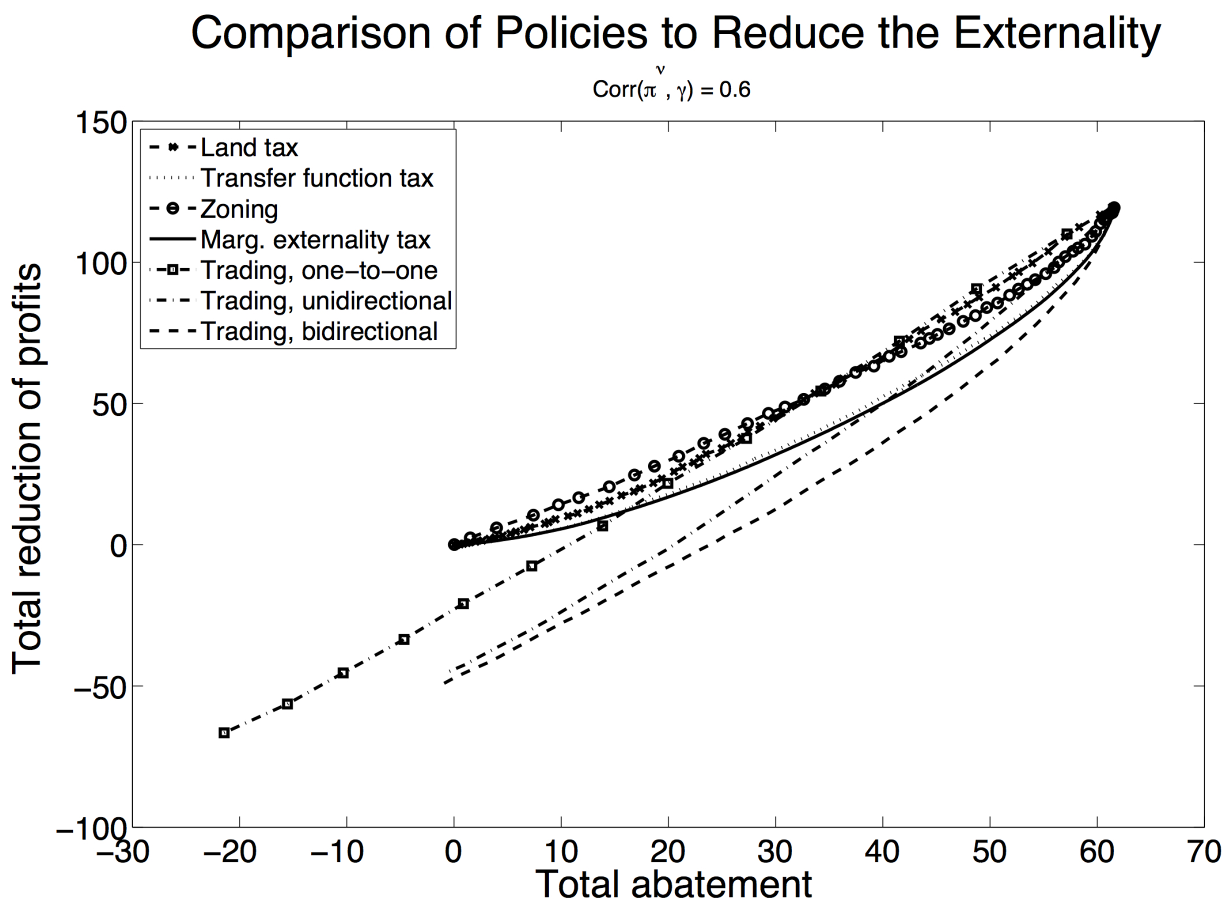

Figure 9: Comparison of Alternative Policies Under a Strong, Positive Correlation Between π^{ν} and γ

Each policy is fairly linear in costs with respect to abatement level, and yet there are more noticeable differences in policy costs. One-to-one trading results in disastrous consequences for abatement, and is quickly outperformed by tax policies. In this case, unidirectional trading approximates bidirectional trading, as buyers have higher expected marginal externalities than sellers, resulting in a discounted trading ratio under the unidirectional scheme. Unidirectional and bidirectional trading still outperform the tax policies significantly.

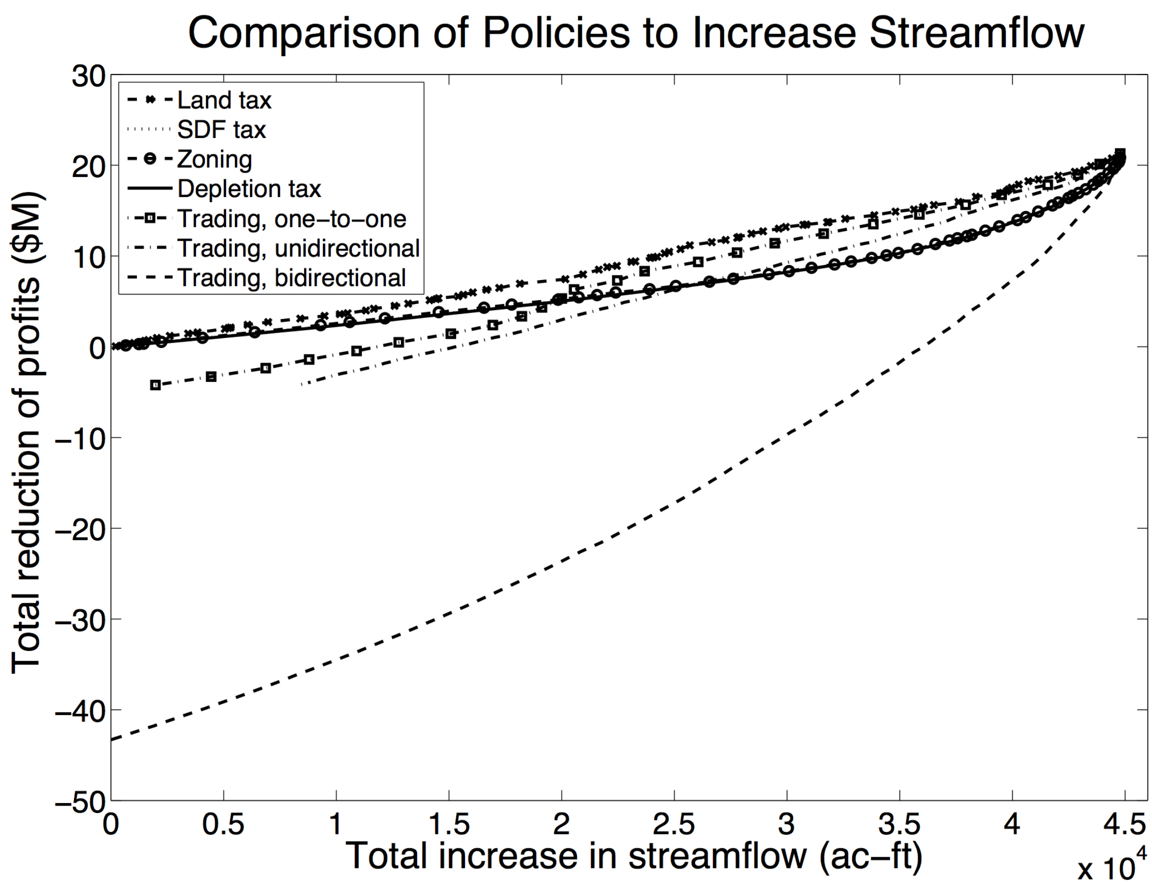

Figure 10: Twin Platte NRD: Policy Costs with Streamflow Enhancements
As restrictions increase, streamflow increases and costs are incurred. Zoning and a tax on the SDF perform as well as the depletion tax, with perfect information. Tradable permit systems can result in economic gains that could not be realized through even the most effective tax policy.

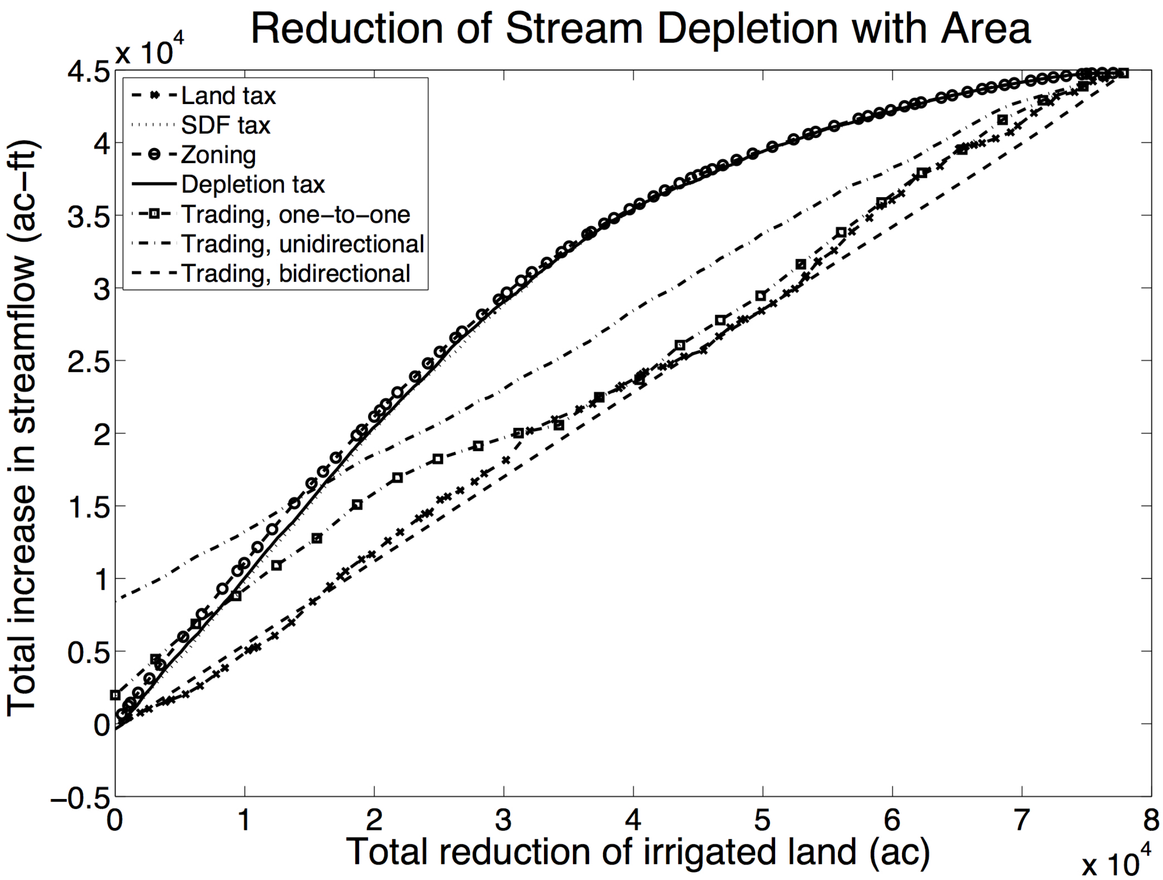

Figure 11: Twin Platte NRD: Streamflow Enhancements with Reductions in Irrigated Land Using different policy mechanisms, the total quantity of irrigated land must be reduced by varying amounts to achieve the same streamflow target. Zoning, the SDF tax, and the depletion tax consistently perform very well, as they always push out the most damaging lands first, and therefore have high abatement to retired land ratios.

Appendix A: Supplemental Figures

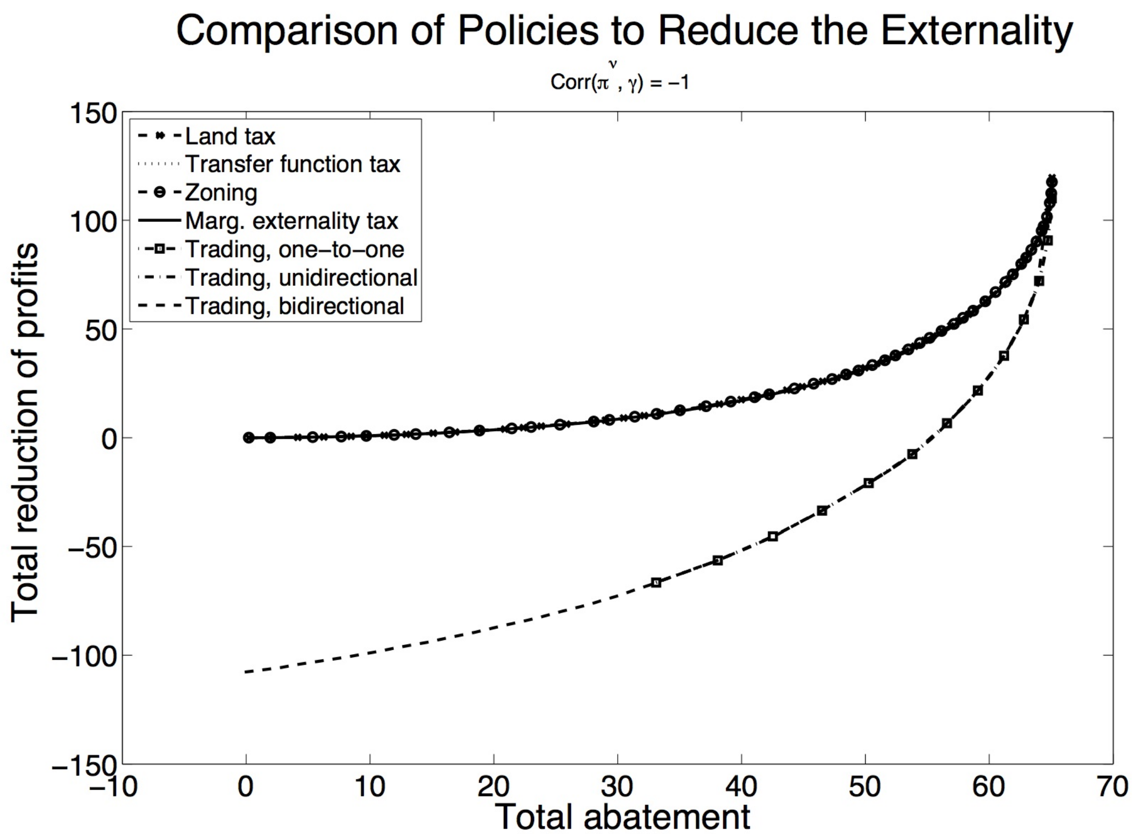

Figure A.1: Comparison of Alternative Policies Under a Perfectly Negative Correlation Between π^{ν} and γ
In this case, all trading policies overlap with one another and all tax policies overlap with one another. Trading policies are much more cost-effective.

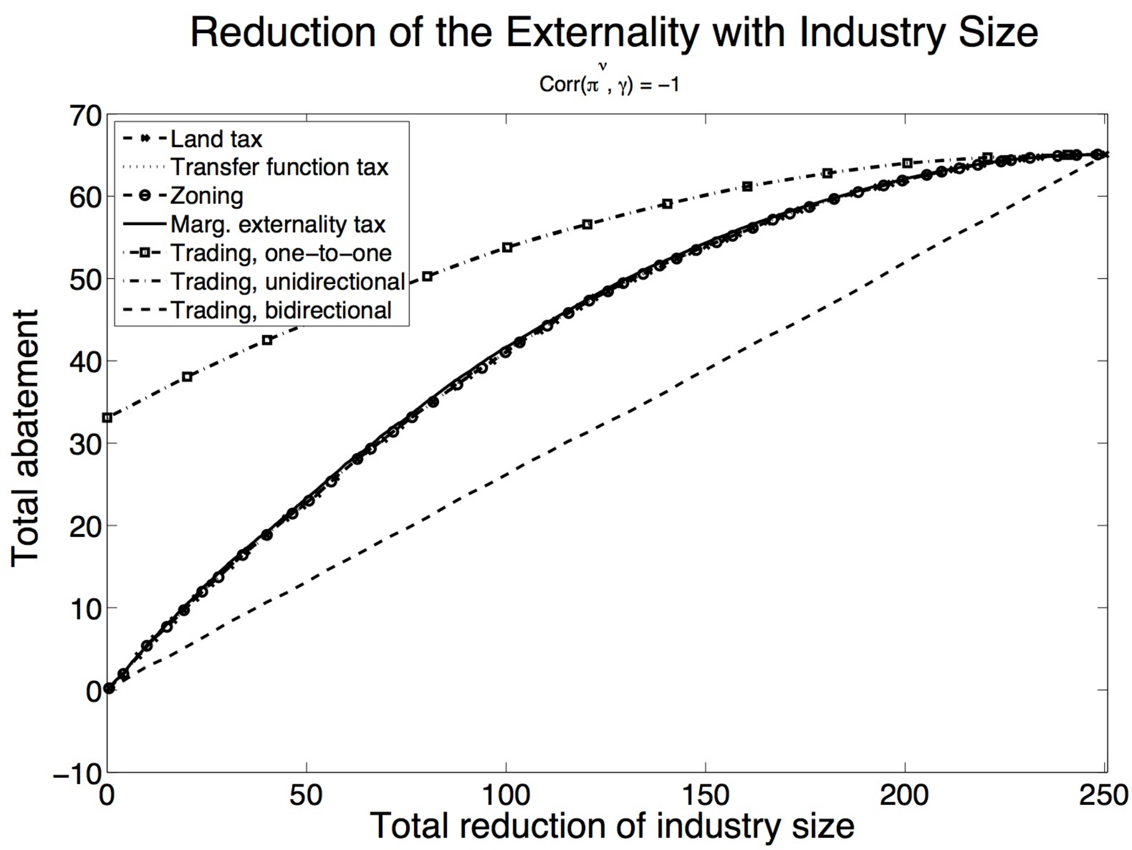

Figure A.2: Reductions of the Externality with Reductions in Industry Size for a Perfectly Negative Correlation Between π^{ν} and γ
In this case, unidirectional and one-to-one trading schemes overlap; tax policies overlap; bidirectional trading is linear (as it is across all correlations).

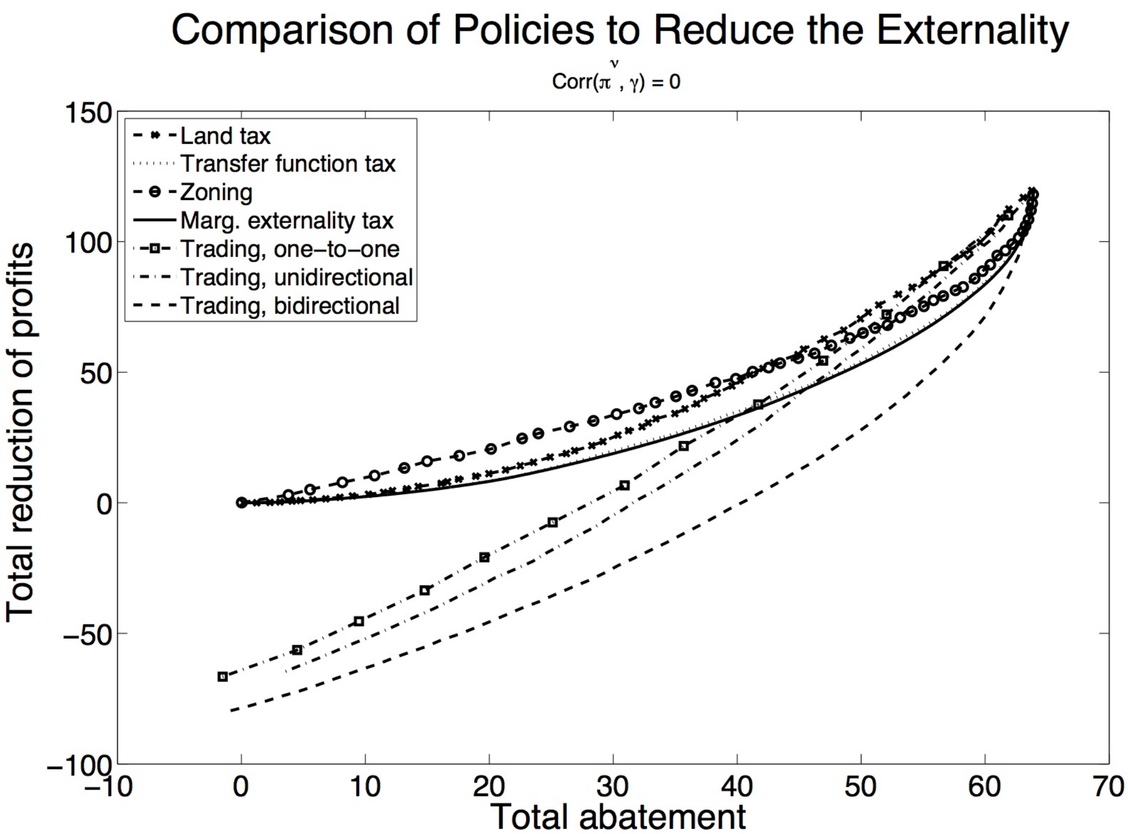

Figure A.3: Comparison of Alternative Policies with No Correlation Between π^{ν} and γ

Figure A.4: Reductions of the Externality with Reductions in Industry Size with No Negative Correlation Between π^{ν} and γ

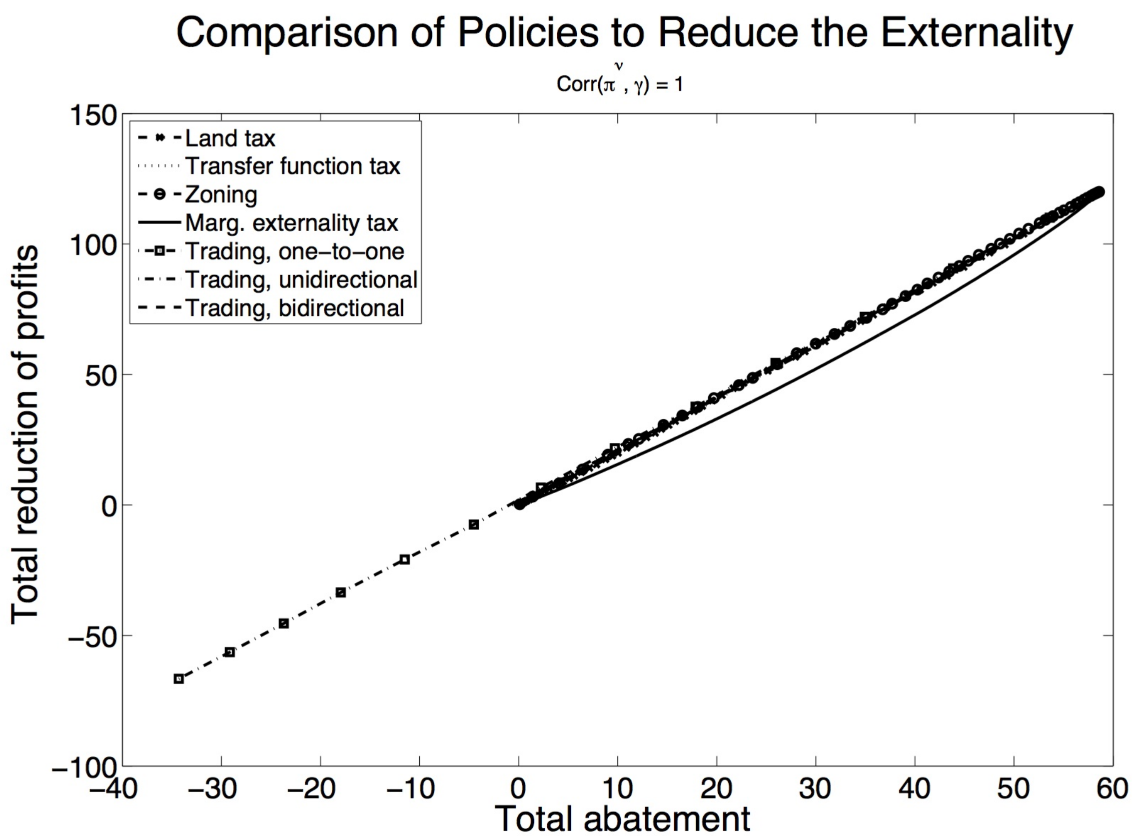

Figure A.5: Comparison of Alternative Policies Under a Perfectly Positive Correlation Between π^{ν} and γ

In this case, tax and trading policies overlap greatly with one another and a strong, linear relationship exists between abatement and policy cost.

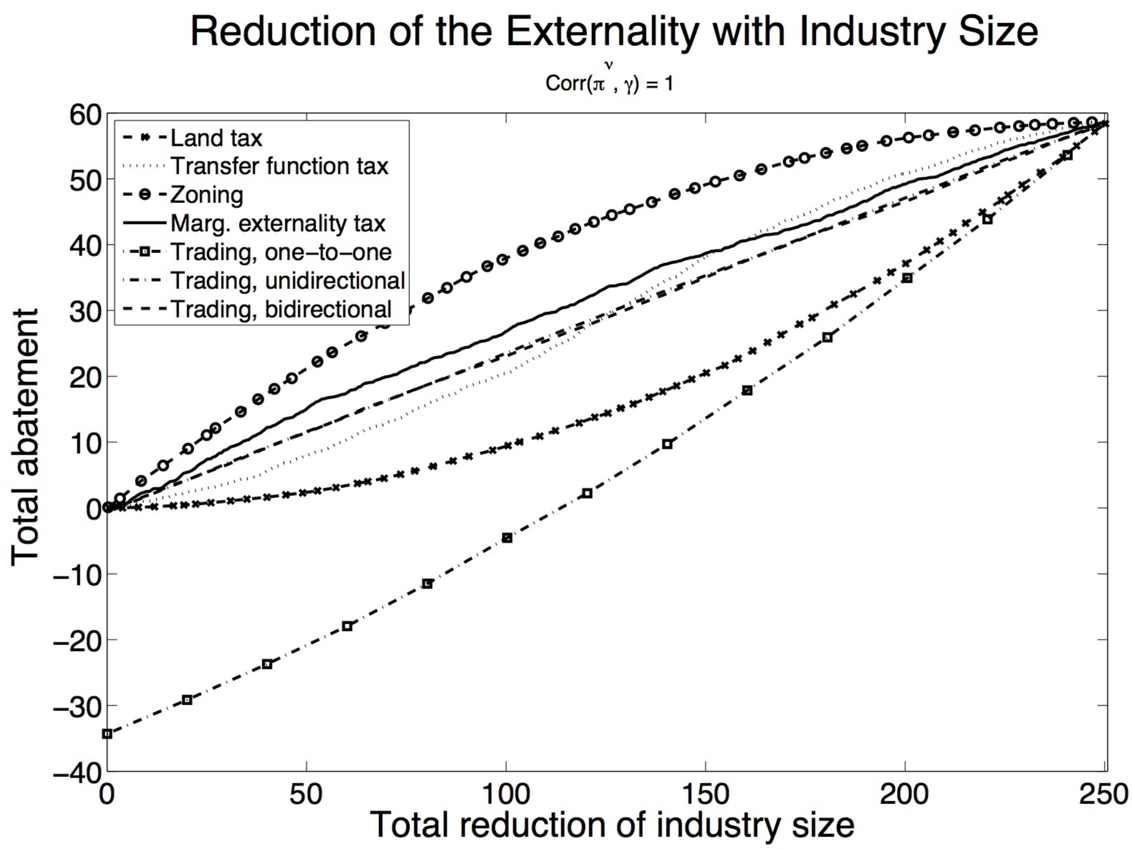

Figure A.6: Reductions of the Externality with Reductions in Industry Size for a Perfectly Positive Correlation Between π^ν and γ

Appendix B: Computer Code

The following codes were used for simulating the policy analyses using the synthetic data and the Twin Platte NRD data. The codes are quite similar, only with differences in generation.

Random Simulation

```
%Comparing policies in a microparameter framework
%Policies include zoning, SD tax, input tax, 1:1 trading, bi-directional ...
    and uni-directional SDF trading
%Written by Richael K. Young, December 2013

%http://comisef.wikidot.com/tutorial:correlateduniformvariates
clear all
close all force
close all hidden

tic

% generate normals
n = 500;
mu = 0.5;
sd = 0.1;
XI = [mu + sd*randn(n,1) randn(n,3)];
XD = [mu + sd*randn(n,1) randn(n,3)];

% desired correlation
```

```
% (1) water usage (2) change in yields, (3) SDF, (4) irrigated acres
V1 = 1;
V2 = V1;
V3 = V1;
V4 = V1;

C12 = 0;
C13 = 0;
C14 = 0;
C23 = 0;
C24 = 0;
C34 = 0;

%Correlation coefficients analyzed
    %cc = -1:0.2:1;
    %cc = [-0.6 0 0.6];
    %cc = meshgrid(cc);
    cc = [-0.6 0.6];
    steps_cc = length(cc);

%Increasing regulation
    perc_ret = (0:0.02:1)';  %percentage of retired permits
    steps_ret = length(perc_ret);

%Preallocation
    IRR = zeros(n,3,steps_cc);
    DRY = zeros(n,3,steps_cc);

    total_water = zeros(steps_cc,1);
    total_acres = zeros(steps_cc,1);
    total_sd = zeros(steps_cc,1);
    wtd_pump = zeros(steps_cc,1);

    %Tax policies
    T_ret = zeros(n,6,steps_cc);  %land tax
    Z_ret = zeros(n,6,steps_cc);  %zoning
```

```
S_ret = zeros(n,6,steps_cc);  %SDF tax
W_ret = zeros(n,6,steps_cc);  %water tax
P_ret = zeros(n,6,steps_cc);  %Pigouvian tax

%Trading, 1:1
vol_11 = zeros(steps_ret,1,steps_cc);   %volume of transacted permits (...
   acres)
acr_11 = zeros(steps_ret,1,steps_cc);   %acres retired
Esdr_11 = zeros(steps_ret,1,steps_cc);  %expected stream depletion ...
   change (mean pumping*SDF*area)
Asdr_11 = zeros(steps_ret,1,steps_cc);  %actual stream depletion change...
    (SD/ac*area)
dyd_11 = zeros(steps_ret,1,steps_cc);   %total increase of yield (bu/ac...
    * ac)
wat_11 = zeros(steps_ret,1,steps_cc);   %average water usage at this ...
   level of abatement
sda_11 = zeros(steps_ret,1,steps_cc);   %average stream depletion per ...
   acre at this level of abatement
prc_11 = zeros(steps_ret,2,steps_cc);   %price of permits to sellers, ...
   buyers

%SDF trading: bi-directional
vol_2d = zeros(steps_ret,2,steps_cc);   %volume of acres bought, volume...
    of acres sold
acr_2d = zeros(steps_ret,1,steps_cc);   %acres retired
Esdr_2d = zeros(steps_ret,1,steps_cc);  %expected stream depletion ...
   reduction (mu * SDF * area)
Asdr_2d = zeros(steps_ret,1,steps_cc);  %actual stream depletion ...
   reduction (SD/ac * area)
dyd_2d = zeros(steps_ret,1,steps_cc);   %total decrease of yield (bu/ac...
    * ac)
wat_2d = zeros(steps_ret,1,steps_cc);   %average water usage per acre ...
   at this level of abatement
sda_2d = zeros(steps_ret,1,steps_cc);   %average stream depletion per ...
   acre at this level of abatement
```

```
    prc_2d = zeros(steps_ret,2,steps_cc);   %price to sellers, buyers at ... this level of abatement

    %Trading, 1d
    vol_1d = zeros(steps_ret,2,steps_cc);   %volume of acres bought, volume... of acres sold
    acr_1d = zeros(steps_ret,1,steps_cc);   %acres retired
    Esdr_1d = zeros(steps_ret,1,steps_cc);  %expected stream depletion ... reduction (mu * SDF * area)
    Asdr_1d = zeros(steps_ret,1,steps_cc);  %actual stream depletion ... reduction (SD/ac * area)
    dyd_1d = zeros(steps_ret,1,steps_cc);   %total decrease of yield (bu/ac... * ac)
    wat_1d = zeros(steps_ret,1,steps_cc);   %average water use per acre
    sda_1d = zeros(steps_ret,1,steps_cc);   %average stream depletion per ... acre
    prc_1d = zeros(steps_ret,2,steps_cc);   %blended sellers', buyers' ... prices


%Change correlation between SDF and change in yields
for k = 1:steps_cc

    %C23 = cc(k); %for SDF
    C12 = cc(k); %for water usage

    M = [V1  C12  C13  C14;
        C12  V2   C23  C24;
        C13  C23  V3   C34;
        C14  C24  C34  V4 ];

    % adjust correlations for uniforms
    for i = 1:4
        for j = max(i,2):4
            if i ≠ j
                M(i, j) = 2 * sin(pi * M(i, j) / 6);
```

```
            M(j, i) = 2 * sin(pi * M(j, i) / 6);
        end
    end
end

% induce correlation, check correlations
C = chol(M);
YI = XI * C;
YD = XD * C;

YI(:,2:4) = normcdf(YI(:,2:4));
YD(:,2:4) = normcdf(YD(:,2:4));

%reorder
YI(:,1:4) = [YI(:,2), YI(:,3), YI(:,4), YI(:,1)];
YD(:,1:4) = [YD(:,2), YD(:,3), YD(:,4), YD(:,1)];

total_water(k) = sum(YI(:,4).*YI(:,3));
total_acres(k) = sum(YI(:,3));
total_sd(k) = sum(YI(:,2).*YI(:,4).*YI(:,3));
wtd_pump(k) = total_water(k)./total_acres(k);

%create YD Column 5 for SD/ac
YD(:,5) = YD(:,2).*YD(:,4);

%create additional columns for zoning, land tax, and SDF tax
YI(:,1:9) = [YI(:,1:4) YI(:,2)./YI(:,1) YI(:,1).*YI(:,3) YI(:,2).*YI...
    (:,4) YI(:,2).*YI(:,4).*YI(:,3) wtd_pump(k)*YI(:,2).*YI(:,3)];
YI(:,10) = YI(:,4)./YI(:,1);
YI(:,11) = YI(:,7)./YI(:,1);
%Column 1 is the output (yield) per unit input (irrigated acres)
%Column 2 is the stream depletion factor
%Column 3 is the normalized density (proportion of irrigated to total
%available land
%Column 4 is the irrigation use
%Column 5 is the ratio of SDF : change in yield
```

```
%Column 6 is the total yield, yd*area
%Column 7 is the SD per acre = SDF*irrigation use
%Column 8 is the actual stream depletion, SD/ac*area
%Column 9 is the expected stream depletion, SDF*area*mean

IRR(:,:,k) = [YI(:,1), YI(:,2), YI(:,3)];
DRY(:,:,k) = [YD(:,1), YD(:,2), YD(:,3)];

%Sort sections by their selection for retirement based on policy tool
%T: input tax, remove lowest change in yield first
%Z: zoning, remove highest SDF first
%S: stream depletion tax, remove highest SDF/change in yd first
T_rank = sortrows(YI,1);
Z_rank = sortrows(YI,-2);
S_rank = sortrows(YI,-5);
W_rank = sortrows(YI,-10);  %water tax
P_rank = sortrows(YI,-11);  %pollution tax

%Column 1 is the total reduction in yield
%Column 2 is the actual reduction in stream depletion, or increase in
%streamflow
%Column 3 is the total reduction in irrigated land
%Column 4 is the expected reduction in stream depletion
T_ret(:,:,k) = [cumsum(T_rank(:,6)) cumsum(T_rank(:,8)) cumsum(T_rank...
    (:,3)) cumsum(T_rank(:,9)) zeros(n,2)];
Z_ret(:,:,k) = [cumsum(Z_rank(:,6)) cumsum(Z_rank(:,8)) cumsum(Z_rank...
    (:,3)) cumsum(Z_rank(:,9)) zeros(n,2)];
S_ret(:,:,k) = [cumsum(S_rank(:,6)) cumsum(S_rank(:,8)) cumsum(S_rank...
    (:,3)) cumsum(S_rank(:,9)) zeros(n,2)];
W_ret(:,:,k) = [cumsum(W_rank(:,6)) cumsum(W_rank(:,8)) cumsum(W_rank...
    (:,3)) cumsum(W_rank(:,9)) zeros(n,2)];
P_ret(:,:,k) = [cumsum(P_rank(:,6)) cumsum(P_rank(:,8)) cumsum(P_rank...
    (:,3)) cumsum(P_rank(:,9)) zeros(n,2)];
%Column 5 is the new average water use per acre, having removed field
%Column 6 is the new average stream depletion per acre, having field ...
    removed
```

```
T_ret(:,5,k) = (total_water(k)*ones(n,1) - cumsum(T_rank(:,4).*T_rank...
    (:,3)))./(total_acres(k)*ones(n,1) - cumsum(T_rank(:,3)));
Z_ret(:,5,k) = (total_water(k)*ones(n,1) - cumsum(Z_rank(:,4).*Z_rank...
    (:,3)))./(total_acres(k)*ones(n,1) - cumsum(Z_rank(:,3)));
S_ret(:,5,k) = (total_water(k)*ones(n,1) - cumsum(S_rank(:,4).*S_rank...
    (:,3)))./(total_acres(k)*ones(n,1) - cumsum(S_rank(:,3)));
W_ret(:,5,k) = (total_water(k)*ones(n,1) - cumsum(W_rank(:,4).*W_rank...
    (:,3)))./(total_acres(k)*ones(n,1) - cumsum(W_rank(:,3)));
P_ret(:,5,k) = (total_water(k)*ones(n,1) - cumsum(P_rank(:,4).*P_rank...
    (:,3)))./(total_acres(k)*ones(n,1) - cumsum(P_rank(:,3)));
T_ret(:,6,k) = (total_sd(k)*ones(n,1) - cumsum(T_rank(:,7).*T_rank(:,3)...
    ))./(total_acres(k)*ones(n,1) - cumsum(T_rank(:,3)));
Z_ret(:,6,k) = (total_sd(k)*ones(n,1) - cumsum(Z_rank(:,7).*Z_rank(:,3)...
    ))./(total_acres(k)*ones(n,1) - cumsum(Z_rank(:,3)));
S_ret(:,6,k) = (total_sd(k)*ones(n,1) - cumsum(S_rank(:,7).*S_rank(:,3)...
    ))./(total_acres(k)*ones(n,1) - cumsum(S_rank(:,3)));
W_ret(:,6,k) = (total_sd(k)*ones(n,1) - cumsum(W_rank(:,7).*W_rank(:,3)...
    ))./(total_acres(k)*ones(n,1) - cumsum(W_rank(:,3)));
P_ret(:,6,k) = (total_sd(k)*ones(n,1) - cumsum(P_rank(:,7).*P_rank(:,3)...
    ))./(total_acres(k)*ones(n,1) - cumsum(P_rank(:,3)));


%%%%%%%%%%%%%%%%%%%%%%%%%%
% Tradable permit systems %
%%%%%%%%%%%%%%%%%%%%%%%%%%
%1:1 trading

for kk = 1:steps_ret
    ret_11 = [YI(:,1:2), perc_ret(kk)*YI(:,3),YI(:,4), YI(:,7)];
    wi_11 = [YI(:,1:2), (1 - perc_ret(kk))*YI(:,3), YI(:,4), YI(:,7)];
    wo_11 = [YD; ret_11];

    fields_irr = size(wi_11,1); %fields with irrigation rights
    fields_dry = size(wo_11,1); %fields without irrigation rights

    %Preallocate and find effective bid
```

```
        eff_bid_11 = zeros(fields_irr, fields_dry);  %effective bid between...
            each buyer and seller, weighted by SDF

        for i = 1:fields_irr     %sellers
            for j = 1:fields_dry %buyers
                if wo_11(j,3) > 0
                    %if there is positive acreage, there is a demand to ...
                        buy.
                    %otherwise, eff_bid = 0.
                    eff_bid_11(i,j) = max(wo_11(j,1) - wi_11(i,1),0);
                    %the difference between the yield values
                end
            end
        end

        [ranked_11 index_11] = sortrows(reshape(eff_bid_11,[],1),-1);
        %properties of trades
        %(1) total increase in yields
        %(2) expected change in SD
        %(3) actual change in SD
        %(4) acres sold
        %(5) acres bought
        %(6) increase in water usage per acre
        %(7) increase in stream depletion per acre
        %(8) price to seller = price to buyer for 1:1 trades
        trades_11 = zeros(size(index_11,1),7);

        %tracks acreage
        purch_11 = zeros(fields_dry,1);
        sold_11 = zeros(fields_irr,1);

        for i = 1:length(index_11)
            if ranked_11(i) > 0
                seller_index = 1 + rem(index_11(i) + fields_irr - 1, ...
                    fields_irr);
                buyer_index = ceil(index_11(i)/fields_irr);
```

```
            %seller's constraint
            S_con_11 = (wi_11(seller_index,3)-sold_11(seller_index,1));
            %buyer's constraint
            B_con_11 = (wo_11(buyer_index,3)-purch_11(buyer_index,1));
            %trade max acres between constraints
            const_11 = min([S_con_11 B_con_11]);
            trades_11(i,4) = const_11;
            trades_11(i,5) = const_11;
            trades_11(i,6) = wo_11(buyer_index,4)*trades_11(i,5) - ...
                wi_11(seller_index,4)*trades_11(i,4);
            trades_11(i,7) = wo_11(buyer_index,5)*trades_11(i,5) - ...
                wi_11(seller_index,5)*trades_11(i,4);
            trades_11(i,8) = (wi_11(seller_index,1)*trades_11(i,4) + ...
                wo_11(buyer_index,1)*trades_11(i,5))/(2*trades_11(i,4))...
                ;
            trades_11(i,1) = wo_11(buyer_index,1)*trades_11(i,5) - ...
                wi_11(seller_index,1)*trades_11(i,4);
            trades_11(i,2) = wtd_pump(k)*(wo_11(buyer_index,2)*...
                trades_11(i,5) - wi_11(seller_index,2)*trades_11(i,4));
            trades_11(i,3) = wo_11(buyer_index,5)*trades_11(i,5) - ...
                wi_11(seller_index,5)*trades_11(i,4);
            %update buyer
            purch_11(buyer_index,1) = purch_11(buyer_index,1) + ...
                trades_11(i,5);
            %update seller
            sold_11(seller_index,1) = sold_11(seller_index,1) + ...
                trades_11(i,4);
        end
    end
    trades_11(isnan(trades_11)) = 0;
    %for final output
    acr_11(kk,1,k) = sum(ret_11(:,3));
    dyd_11(kk,1,k) = sum(ret_11(:,1).*ret_11(:,3)) - sum(trades_11(:,1)...
        );
    Esdr_11(kk,1,k) = wtd_pump(k)*sum(ret_11(:,2).*ret_11(:,3)) - sum(...
        trades_11(:,2));
```

```
        Asdr_11(kk,1,k) = sum(ret_11(:,5).*ret_11(:,3)) - sum(trades_11...
            (:,3));
        vol_11(kk,1:2,k) = sum(trades_11(:,4:5));
        wat_11(kk,1,k) = (sum(wi_11(:,3).*wi_11(:,4)) + sum(trades_11(:,6))...
            )/sum(wi_11(:,3));
        sda_11(kk,1,k) = (sum(wi_11(:,3).*wi_11(:,5)) + sum(trades_11(:,7))...
            )/sum(wi_11(:,3));
        prc_11(kk,1,k) = sum(trades_11(:,8))/vol_11(kk,1,k);
    end

    %Bidirectional trading
    for kk = 1:steps_ret
        ret_2d = [YI(:,1:2), perc_ret(kk)*YI(:,3), YI(:,4), YI(:,7)];
        wi_2d = [YI(:,1:2), (1 - perc_ret(kk))*YI(:,3), YI(:,4), YI(:,7)];
        wo_2d = [YD; ret_2d];

        fields_irr = size(wi_2d,1);
        fields_dry = size(wo_2d,1);

        %Preallocate and find effective bid
        eff_bid_2d = zeros(fields_irr, fields_dry);  %effective bid between...
             each buyer and seller, weighted by SDF

        for i = 1:fields_irr     %sellers
            for j = 1:fields_dry %buyers
                if wo_2d(j,3) > 0
                    %if there is positive acreage, there is a demand to ...
                        buy.
                    %otherwise, eff_bid = 0.
                    eff_bid_2d(i,j) = max(wo_2d(j,1) - wi_2d(i,1)*wo_2d(j...
                        ,2)/wi_2d(i,2),0);
                    %related by y = mx + b, where m is the seller's sdf/yd,...
                         b is the
                    %y-intercept for the buyer using that seller's sdf/yd. ...
                        then set y =
                    %0 and solve for x, the effective bid.
```

```
            end
        end
    end

    [ranked_2d index_2d] = sortrows(reshape(eff_bid_2d,[],1),-1);
    %properties of trades
    %(1) total increase in yields
    %(2) expected change in SD
    %(3) actual change in SD
    %(4) acres sold
    %(5) acres bought
    %(6) for looking at water usage per acre
    %(7) for looking at stream depletion per acre
    %(8) seller's price * sold acres
    %(9) buyer's price * purchased acres
    trades_2d = zeros(size(index_2d,1),9);

    %tracks acreage
    purch_2d = zeros(fields_dry,1);
    sold_2d = zeros(fields_irr,1);

    for i = 1:length(index_2d)
        if ranked_2d(i) > 0
            seller_index = 1 + rem(index_2d(i) + fields_irr - 1, ...
                fields_irr);
            buyer_index = ceil(index_2d(i)/fields_irr);
            %seller's constraint
            S_con = (wi_2d(seller_index,3)-sold_2d(seller_index,1))*...
                wi_2d(seller_index,2);
            %buyer's constraint
            B_con = (wo_2d(buyer_index,3)-purch_2d(buyer_index,1))*...
                wo_2d(buyer_index,2);
            %trade max acres between constraints
            [const_2d IX] = min([S_con B_con]);
            if IX == 1
                %S_con binds
```

```
                trades_2d(i,4) = wi_2d(seller_index,3)-sold_2d(...
                    seller_index,1);
                trades_2d(i,5) = const_2d/wo_2d(buyer_index,2);
            else
                %B_con binds
                trades_2d(i,4) = const_2d/wi_2d(seller_index,2);
                trades_2d(i,5) = wo_2d(buyer_index,3)-purch_2d(...
                    buyer_index,1);
            end
            trades_2d(i,6) = wo_2d(buyer_index,4)*trades_2d(i,5) - ...
                wi_2d(seller_index,4)*trades_2d(i,4);
            trades_2d(i,7) = wo_2d(buyer_index,5)*trades_2d(i,5) - ...
                wi_2d(seller_index,5)*trades_2d(i,4);
            trades_2d(i,8) = (wi_2d(seller_index,1)*trades_2d(i,4) + ...
                wo_2d(buyer_index,1)*trades_2d(i,5))/(2*trades_2d(i,4))...
                ;
            trades_2d(i,9) = (wi_2d(seller_index,1)*trades_2d(i,4) + ...
                wo_2d(buyer_index,1)*trades_2d(i,5))/(2*trades_2d(i,5))...
                ;
            trades_2d(i,1) = wo_2d(buyer_index,1)*trades_2d(i,5) - ...
                wi_2d(seller_index,1)*trades_2d(i,4);
            trades_2d(i,2) = wtd_pump(k)*(wo_2d(buyer_index,2)*...
                trades_2d(i,5) - wi_2d(seller_index,2)*trades_2d(i,4));
            trades_2d(i,3) = wo_2d(buyer_index,5)*trades_2d(i,5) - ...
                wi_2d(seller_index,5)*trades_2d(i,4);
            %update buyer
            purch_2d(buyer_index,1) = purch_2d(buyer_index,1) + ...
                trades_2d(i,5);
            %update seller
            sold_2d(seller_index,1) = sold_2d(seller_index,1) + ...
                trades_2d(i,4);
        end
    end
    trades_2d(isnan(trades_2d)) = 0;
    %for final output
    acr_2d(kk,1,k) = sum(ret_2d(:,3));
```

```
        dyd_2d(kk,1,k) = sum(ret_2d(:,1).*ret_2d(:,3)) - sum(trades_2d(:,1)...
           );
        Esdr_2d(kk,1,k) = wtd_pump(k)*sum(ret_2d(:,2).*ret_2d(:,3)) - sum(...
           trades_2d(:,2));
        Asdr_2d(kk,1,k) = sum(ret_2d(:,5).*ret_2d(:,3)) - sum(trades_2d...
           (:,3));
        vol_2d(kk,1:2,k) = sum(trades_2d(:,4:5));
        wat_2d(kk,1,k) = (sum(wi_2d(:,3).*wi_2d(:,4)) + sum(trades_2d(:,6))...
           )/(sum(wi_2d(:,3)) + sum(trades_2d(:,5)) - sum(trades_2d(:,4)))...
           ;
        sda_2d(kk,1,k) = (sum(wi_2d(:,3).*wi_2d(:,5)) + sum(trades_2d(:,7))...
           )/(sum(wi_2d(:,3)) + sum(trades_2d(:,5)) - sum(trades_2d(:,4)))...
           ;
        prc_2d(kk,1:2,k) = [sum(trades_2d(:,8))/vol_2d(kk,1,k), sum(...
           trades_2d(:,9))/vol_2d(kk,2,k)];
    end

    %Unidirectional trading
    for kk = 1:steps_ret
        ret_1d = [YI(:,1:2), perc_ret(kk)*YI(:,3), YI(:,4), YI(:,7)];
        wi_1d = [YI(:,1:2), (1 - perc_ret(kk))*YI(:,3), YI(:,4), YI(:,7)];
        wo_1d = [YD; ret_1d];

        fields_irr = size(wi_1d,1);
        fields_dry = size(wo_1d,1);

        %Preallocate and find effective bid
        eff_bid_1d = zeros(fields_irr,fields_dry);    %effective bid ...
           between each buyer and seller, weighted by SDF
        bid_type = zeros(fields_irr,fields_dry);      %zero for 1:1 trade, ...
           1 if discounted

        for i = 1:fields_irr     %sellers
            for j = 1:fields_dry %buyers
                if wo_1d(j,3) > 0
```

```
                %if there is positive acreage, there is a demand to ...
                    buy.
                %otherwise, eff_bid = 0.
                if wi_1d(i,2) ≥ wo_1d(j,2)
                    %SDF of seller is less than SDF of buyer, 1:1 trade
                    eff_bid_1d(i,j) = max(0, wo_1d(j,1) - wi_1d(i,1));
                else
                    bid_type(i,j) = 1;
                    eff_bid_1d(i,j) = max(wo_1d(j,1) - wi_1d(i,1)*wo_1d...
                        (j,2)/wi_1d(i,2),0);
                    %related by y = mx + b, where m is the seller's sdf...
                        /yd, b is the
                    %y-intercept for the buyer using that seller's sdf/...
                        yd. then set y =
                    %0 and solve for x, the effective bid.
                end
            end
        end
    end

    [ranked_1d index_1d] = sortrows(reshape(eff_bid_1d,[],1),-1);
    %properties of trades
    %(1) total increase in yields
    %(2) expected change in SD
    %(3) actual change in SD
    %(4) acres sold
    %(5) acres bought
    %(6) for checking water use per acre
    %(7) for checking stream depletion per acre
    %(8) seller's price * sold acres
    %(9) buyer's price * purchased acres
    trades_1d = zeros(size(index_1d,1),9);

    %tracks acreage
    purch_1d = zeros(fields_dry,1);
    sold_1d = zeros(fields_irr,1);
```

```
        for i = 1:length(index_1d)
            if ranked_1d(i) > 0
                buyer_index = ceil(index_1d(i)/fields_irr);
                seller_index = 1 + rem(index_1d(i) + fields_irr - 1, ...
                    fields_irr);
                if bid_type(index_1d(i)) == 0
                    %seller's constraint
                    S_con_1d = (wi_1d(seller_index,3)-sold_1d(seller_index...
                        ,1));
                    %buyer's constraint
                    B_con_1d = (wo_1d(buyer_index,3)-purch_1d(buyer_index...
                        ,1));
                    const_1d = min([S_con_1d B_con_1d]);
                    trades_1d(i,4) = const_1d;
                    trades_1d(i,5) = const_1d;
                else
                    %seller's constraint
                    S_con_1d = (wi_1d(seller_index,3)-sold_1d(seller_index...
                        ,1))*wi_1d(seller_index,2);
                    %buyer's constraint
                    B_con_1d = (wo_1d(buyer_index,3)-purch_1d(buyer_index...
                        ,1))*wo_1d(buyer_index,2);
                    %trade max acres between constraints
                    [const_1d IX] = min([S_con_1d B_con_1d]);
                    if IX == 1
                        %S_con binds
                        trades_1d(i,4) = wi_1d(seller_index,3)-sold_1d(...
                            seller_index,1);
                        trades_1d(i,5) = const_1d/wo_1d(buyer_index,2);
                    else
                        %B_con binds
                        trades_1d(i,4) = const_1d/wi_1d(seller_index,2);
                        trades_1d(i,5) = wo_1d(buyer_index,3)-purch_1d(...
                            buyer_index,1);
                    end
```

```
            end
            trades_1d(i,6) = wo_1d(buyer_index,4)*trades_1d(i,5) - ...
                wi_1d(seller_index,4)*trades_1d(i,4);
            trades_1d(i,7) = wo_1d(buyer_index,5)*trades_1d(i,5) - ...
                wi_1d(seller_index,5)*trades_1d(i,4);
            trades_1d(i,8) = (wi_1d(seller_index,1)*trades_1d(i,4) + ...
                wo_1d(buyer_index,1)*trades_1d(i,5))/(2*trades_1d(i,4))...
                ;
            trades_1d(i,9) = (wi_1d(seller_index,1)*trades_1d(i,4) + ...
                wo_1d(buyer_index,1)*trades_1d(i,5))/(2*trades_1d(i,5))...
                ;
            trades_1d(i,1) = wo_1d(buyer_index,1)*trades_1d(i,5) - ...
                wi_1d(seller_index,1)*trades_1d(i,4);
            trades_1d(i,2) = wtd_pump(k)*(wo_1d(buyer_index,2)*...
                trades_1d(i,5) - wi_1d(seller_index,2)*trades_1d(i,4));
            trades_1d(i,3) = wo_1d(buyer_index,5)*trades_1d(i,5) - ...
                wi_1d(seller_index,5)*trades_1d(i,4);
            %update buyer
            purch_1d(buyer_index,1) = purch_1d(buyer_index,1) + ...
                trades_1d(i,5);
            %update seller
            sold_1d(seller_index,1) = sold_1d(seller_index,1) + ...
                trades_1d(i,4);
        end
    end
    trades_1d(isnan(trades_1d)) = 0;
    %for final output
    acr_1d(kk,1,k) = sum(ret_1d(:,3));
    dyd_1d(kk,1,k) = sum(ret_1d(:,1).*ret_1d(:,3)) - sum(trades_1d(:,1)...
        );
    Esdr_1d(kk,1,k) = wtd_pump(k)*sum(ret_1d(:,2).*ret_1d(:,3)) - sum(...
        trades_1d(:,2));
    Asdr_1d(kk,1,k) = sum(ret_1d(:,5).*ret_1d(:,3)) - sum(trades_1d...
        (:,3));
    vol_1d(kk,1:2,k) = sum(trades_1d(:,4:5));
```

```
        wat_1d(kk,1,k) = (sum(wi_1d(:,3).*wi_1d(:,4)) + sum(trades_1d(:,6))...
            )/(sum(wi_1d(:,3)) + sum(trades_1d(:,5)) - sum(trades_1d(:,4)))...
            ;
        sda_1d(kk,1,k) = (sum(wi_1d(:,3).*wi_1d(:,5)) + sum(trades_1d(:,7))...
            )/(sum(wi_1d(:,3)) + sum(trades_1d(:,5)) - sum(trades_1d(:,4)))...
            ;
        prc_1d(kk,1:2,k) = [sum(trades_1d(:,8))/vol_1d(kk,1,k), sum(...
            trades_1d(:,9))/vol_1d(kk,2,k)];
    end

end

toc

set(0,'DefaultAxesLineStyleOrder','-|--|-.')
set(0,'DefaultAxesColorOrder',[0 0 0])

for k = 1:steps_cc
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %Irrigated/ Dryland Properties%
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    formspec1 = 'rand_ext_properties%d';
    fnam1 = sprintf(formspec1,k);
    h1 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], '...
        Visible', 'off');
    subplot(1,2,1);
    scatter(IRR(:,1,k),IRR(:,2,k),IRR(:,3,k)*50,'k','LineWidth',2)
    %axis([0 1 0 1])
    set(gca,'FontSize',20)
    ylabel('\fontsize{24} Transfer function')
    xlabel('\fontsize{24} Marginal value')
    title({'\fontsize{28} Damaging Firms',['\fontsize{14} Corr(\pi^\nu, \...
        gamma) = ',num2str(cc(k))]})
    subplot(1,2,2)
    scatter(DRY(:,1,k),DRY(:,2,k),DRY(:,3,k)*50,'k','LineWidth',2)
    %axis([0 1 0 1])
```

```
    set(gca,'FontSize',20)
    ylabel('\fontsize{24} Transfer function')
    xlabel('\fontsize{24} Marginal value')
    title({'\fontsize{28} Non-Damaging Firms',['\fontsize{14} Corr(\pi^\nu,...
        \gamma) = ',num2str(cc(k))]})
    print(h1,fnam1,'-depsc')

    formspec1 = 'rand_ext2_properties%d';
    fnam1 = sprintf(formspec1,k);
    h1 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], '...
       Visible', 'off');
    subplot(1,2,1);
    scatter(IRR(:,1,k),mean(IRR(:,2,k)).*IRR(:,2,k),IRR(:,3,k)*50,'k','...
       LineWidth',2)
    %axis([0 1 0 1])
    set(gca,'FontSize',20)
    ylabel('\fontsize{24} Expected marginal externality')
    xlabel('\fontsize{24} Marginal value')
    title({'\fontsize{28} Damaging Firms',['\fontsize{14} Corr(\pi^\nu, \...
       gamma) = ',num2str(cc(k))]})
    subplot(1,2,2)
    scatter(DRY(:,1,k),mean(DRY(:,2,k)).*DRY(:,2,k),DRY(:,3,k)*50,'k','...
       LineWidth',2)
    %axis([0 1 0 1])
    set(gca,'FontSize',20)
    ylabel('\fontsize{24} Expected marginal externality')
    xlabel('\fontsize{24} Marginal value')
    title({'\fontsize{28} Non-Damaging Firms',['\fontsize{14} Corr(\pi^\nu,...
        \gamma) = ',num2str(cc(k))]})
    print(h1,fnam1,'-depsc')
end

for k = 1:steps_cc
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %Another policy comparison, w/o extras%
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
formspec1 = 'rand_ext_micro%d';
fnam1 = sprintf(formspec1,k);
h1 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], '...
    Visible', 'off');
r1 = plot(T_ret(1:8:end,2,k),T_ret(1:8:end,1,k),'--x',S_ret(:,2,k),...
    S_ret(:,1,k),':',Z_ret(1:10:end,2,k),Z_ret(1:10:end,1,k),'--o',...
    P_ret(:,2,k),P_ret(:,1,k),'-',Asdr_11(1:4:end,:,k),dyd_11(1:4:end...
    ,:,k),'-.s',Asdr_1d(:,:,k),dyd_1d(:,:,k),'-.',Asdr_2d(:,:,k),dyd_2d...
    (:,:,k),'--');
r2 = legend('Land tax','Transfer function tax','Zoning','Marg. ...
    externality tax','Trading, one-to-one','Trading, unidirectional','...
    Trading, bidirectional','Location','Northwest');
set(r1,'LineWidth',2)
set(r2,'FontSize',16)
set(gca,'FontSize',20)
title({'\fontsize{28} Comparison of Policies to Reduce the Externality'...
    ,['\fontsize{14} Corr(\pi^\nu, \gamma) = ',num2str(cc(k))]})
%axis([-10 70 -100 160])
xlabel('\fontsize{24} Total abatement')        %abatement
ylabel('\fontsize{24} Total reduction of profits')            %costs
print(h1,fnam1,'-depsc')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Irrigated land and streamflow%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
formspec3 = 'rand_ext_area%d';
fnam3 = sprintf(formspec3,k);
h3 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], '...
    Visible', 'off');
r1 = plot(T_ret(1:8:end,3,k),T_ret(1:8:end,2,k),'--x',S_ret(:,3,k),...
    S_ret(:,2,k),':',Z_ret(1:10:end,3,k),Z_ret(1:10:end,2,k),'--o',...
    P_ret(:,3,k),P_ret(:,2,k),'-',acr_11(1:4:end,:,k),Asdr_11(1:4:end...
    ,:,k),'-.s',acr_1d(:,:,k),Asdr_1d(:,:,k),'-.',acr_2d(:,:,k),Asdr_2d...
    (:,:,k),'--');
r2 = legend('Land tax','Transfer function tax','Zoning','Marg. ...
    externality tax','Trading, one-to-one','Trading, unidirectional','...
```

```
        Trading, bidirectional','Location','Northwest');
    set(r1,'LineWidth',2)
    set(r2,'FontSize',16)
    set(gca,'FontSize',20)
    title({'\fontsize{28} Reduction of the Externality with Industry Size'...
        ,['\fontsize{14} Corr(\pi^\nu, \gamma) = ',num2str(cc(k))]})
    xlim([0 max(total_acres)])
    %axis([0 total_acres -10 70])
    xlabel('\fontsize{24} Total reduction of industry size')   %permits ...
        retired
    ylabel('\fontsize{24} Total abatement')         %abatement
    print(h3,fnam3,'-depsc')
end

%%%%for correlations between water and productivity
for k = 1:steps_cc
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %Another policy comparison, w/o extras%
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    formspec1 = 'rand_input_micro%d';
    fnam1 = sprintf(formspec1,k);
    h1 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], '...
        Visible', 'off');
    r1 = plot(T_ret(1:8:end,2,k),T_ret(1:8:end,1,k),'--x',S_ret(:,2,k),...
        S_ret(:,1,k),':',Z_ret(1:10:end,2,k),Z_ret(1:10:end,1,k),'--o',...
        P_ret(:,2,k),P_ret(:,1,k),'-',Asdr_11(1:4:end,:,k),dyd_11(1:4:end...
        ,:,k),'-.s',Asdr_1d(:,:,k),dyd_1d(:,:,k),'-.',Asdr_2d(:,:,k),dyd_2d...
        (:,:,k),'--');
    r2 = legend('Land tax','Transfer function tax','Zoning','Marg. ...
        externality tax','Trading, one-to-one','Trading, unidirectional','...
        Trading, bidirectional','Location','Northwest');
    set(r1,'LineWidth',2)
    set(r2,'FontSize',16)
    set(gca,'FontSize',20)
    title({'\fontsize{28} Comparison of Policies to Reduce the Externality'...
        ,['\fontsize{20} Corr(\pi^\nu, w) = ',num2str(cc(k))]})
```

```
    %axis([-10 70 -100 160])
    xlabel('\fontsize{24} Total abatement')         %abatement
    ylabel('\fontsize{24} Total reduction of profits')           %costs
    print(h1,fnam1,'-depsc')

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %Irrigated land and streamflow%
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    formspec3 = 'rand_input_area%d';
    fnam3 = sprintf(formspec3,k);
    h3 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], '...
       Visible', 'off');
    r1 = plot(T_ret(1:8:end,3,k),T_ret(1:8:end,2,k),'--x',S_ret(:,3,k),...
       S_ret(:,2,k),':',Z_ret(1:10:end,3,k),Z_ret(1:10:end,2,k),'--o',...
       P_ret(:,3,k),P_ret(:,2,k),'-',acr_11(1:4:end,:,k),Asdr_11(1:4:end...
       ,:,k),'-.s',acr_1d(:,:,k),Asdr_1d(:,:,k),'-.',acr_2d(:,:,k),Asdr_2d...
       (:,:,k),'--');
    r2 = legend('Land tax','Transfer function tax','Zoning','Marg. ...
       externality tax','Trading, one-to-one','Trading, unidirectional','...
       Trading, bidirectional','Location','Northwest');
    set(r1,'LineWidth',2)
    set(r2,'FontSize',16)
    set(gca,'FontSize',20)
    title({'\fontsize{28} Reduction of the Externality with Industry Size'...
       ,['\fontsize{20} Corr(\pi^\nu, w) = ',num2str(cc(k))]})
    xlim([0 max(total_acres)])
    %axis([0 total_acres -10 70])
    xlabel('\fontsize{24} Total reduction of industry size')   %permits ...
       retired
    ylabel('\fontsize{24} Total abatement')         %abatement
    print(h3,fnam3,'-depsc')
end
```

Twin Platte NRD Simulation

Preprocessing of Data

```
%Preprocessing of TPNRD data for microparameter model
%Written by Richael K. Young
clear all

%Bring in the slope statistics
fid1 = fopen('Slope_Stats.csv');
slopes_cell = textscan(fid1,...
    '%f %*f %*d %*d %f %f %f %f %f %*f', 'delimiter',',','HeaderLines',1);
    %(1) id, area, count, area, (2) min, (3) max, (4) range, (5) mean,
    %(6) st dev, sum
fclose(fid1);

slopes = cell2mat(slopes_cell(1:6));
n_slopes = length(slopes);

% %Bring in the certified irrigated acres
% fid2 = fopen('CIA-by-Section.csv');
% Y_cell = textscan(fid2,...
%     '%f %f', 'delimiter',',','HeaderLines',1);
%     %(1) id, (2) area (ac)
% fclose(fid2);
%
% Y = cell2mat(Y_cell(1:2));

%Bring in the big-time data
fid2 = fopen('Sections_DRYIRR.csv');
sections_cell = textscan(fid2,...
    '%f %*f %*f %*f %*f %f %*f %f %f %*f %f %f %f', 'delimiter',',','HeaderLines',1);
    %(1) id, x_co, y_co, pi_irr, pi_dry, (2) mv_irr, total_area,
```

```
    %(3) max_irr_area, (4) ac_irr (currently), ac_dry (currently),
    %(5) irr_in (corn), (6) sdf, (7)sd/ac
fclose(fid2);

sections = cell2mat(sections_cell);
n_sections = length(sections);
sections(:,8) = zeros(n_sections,1);

clear slopes_cell sections_cell fid1 fid2


%Match the files
for i=1:n_sections
    ind_slopes = find(slopes(:,1) == i);
    ind_sections = find(sections(:,1) == i);
    if ind_slopes == ind_sections
        sections(ind_sections,8) = slopes(ind_slopes,3);
    end
end


%Drop sections with slopes > 10% [optional: AND no CIA (grandfathered)]
%sections_rem = find(sections(:,8) > 10 & sections(:,4) == 0);
sections_rem = find(sections(:,8) > 10);
sections_slope = removerows(sections,'ind',sections_rem);
sum(sections_slope(:,4))

sections_final = sections_slope(:,1:7);
csvwrite('SECTIONS_FINAL.csv',sections_final);
%(1) id, (2) mv_irr, (3) max_irr_area, (4) ac_irr, (5) irr_in, corn,
%(6) sdf, (7) sd/ac
```

Simulation

```
%Comparing policies in a microparameter framework
%Policies include zoning, SDF tax, depletion tax, 1:1 trading, bi-...
    directional
%trading, and uni-directional trading
%Written by Richael K. Young, December 2013
%Last modified February 2014

clear all
close all force
close all hidden

%fid1=fopen('TPNRD_microparameter_input.csv');
fid1 = fopen('Sections_FINAL.csv');
X_cell = textscan(fid1,...
    '%*d %f %f %f %f %f %f', 'delimiter',',','HeaderLines',1);
    %(*) id, (1) mv_irr, (2) max_irr_area, (3) ac_irr (currently),
    %(4) irr_in (corn), (5) sdf, (6) sd/ac
fclose(fid1);

X = cell2mat(X_cell(1:6));
X(:,7) = X(:,2) - X(:,3);   %max irrigated area demanded (currently dry)

%Reorder, separate irrigated and dryland fields:
%Column 1 is the output (yield) per unit input (irrigated acres)
%Column 2 is the stream depletion factor
%Column 3 is the land area
%Column 4 is the irrigation requirement
%Column 5 is the stream depletion per acre
XI = [X(:,1) X(:,5) X(:,3) X(:,4) X(:,6)];
XI_rem = find(XI(:,3)≤0);
XI = removerows(XI,'ind',XI_rem);
XD = [X(:,1) X(:,5) X(:,7) X(:,4) X(:,6)];
XD_rem = find(XD(:,3)≤0);
XD = removerows(XD,'ind',XD_rem);

XR = [X(:,1) X(:,5) X(:,7) X(:,4) X(:,6) X(:,3)];
```

```
XR_rem = find(XR(:,6)>0);
XR = removerows(XR,'ind',XR_rem);
XR_rem = find(XR(:,3)≤0);
XR = removerows(XR,'ind',XR_rem);
XR(isnan(XR)) = 0;

clear X_cell fid1 XI_rem XD_rem XR_rem

%Aggregate water usage, land, stream depletion + expected seasonal pumping
total_water = sum(XI(:,4).*XI(:,3));    %sum(water use*irr acres)
total_acres = sum(XI(:,3));             %sum(irr acres)
total_sd = sum(XI(:,5).*XI(:,3));       %sum(SD/ac*irr acres)
wtd_pump = total_water/total_acres;     %total water extracted/ total area ...
    irrigated

YI = [XI(:,1:4), XI(:,2)./XI(:,1), XI(:,1).*XI(:,3), XI(:,5), XI(:,5).*XI...
    (:,3), XI(:,2).*XI(:,3)*wtd_pump];
YI(:,10) = YI(:,4)./YI(:,1);
YI(:,11) = YI(:,7)./YI(:,1);
YI(isnan(YI)) = 0;  %replace NaN with 0
%Column 5 is the ratio of stream depletion : change in yield
%Column 6 is the total margianl profit, profit*area
%Column 7 is the stream depletion per acre, SD/ac
%Column 8 is the actual stream depletion, SD/ac * area
%Column 9 is the expected stream depletion, SDF * area * exp_pump
%Column 10 is water use per acre per change in yield
%Column 11 is stream depletion per acre per change in yield

YD = XD(:,1:5);
YD(isnan(YD)) = 0;  %replace NaN with 0

%Sort sections by their selection for retirement based on policy tool
%T: input tax, remove lowest change in yield first
%Z: zoning, remove highest SDF first
%S: stream depletion tax, remove highest SDF/change in yd first
T_rank = sortrows(YI,1);
```

```
Z_rank = sortrows(YI,-2);
S_rank = sortrows(YI,-5);
W_rank = sortrows(YI,-10);   %water tax
P_rank = sortrows(YI,-11);  %pollution tax

%Column 1 is the total reduction in profit
%Column 2 is the actual reduction in stream depletion, or increase in
%streamflow
%Column 3 is the total reduction in irrigated land
%Column 4 is the expected reduction in stream depletion -- this assumes
%that the SDF is known, which for the land tax is not
%Column 5 is the average water use district-wide
%Column 6 is the average stream depletion district-wide
T_ret = [cumsum(T_rank(:,6)) cumsum(T_rank(:,8)) cumsum(T_rank(:,3)) cumsum...
    (T_rank(:,9)) zeros(size(YI,1),1)];
Z_ret = [cumsum(Z_rank(:,6)) cumsum(Z_rank(:,8)) cumsum(Z_rank(:,3)) cumsum...
    (Z_rank(:,9)) zeros(size(YI,1),1)];
S_ret = [cumsum(S_rank(:,6)) cumsum(S_rank(:,8)) cumsum(S_rank(:,3)) cumsum...
    (S_rank(:,9)) zeros(size(YI,1),1)];
W_ret = [cumsum(W_rank(:,6)) cumsum(W_rank(:,8)) cumsum(W_rank(:,3)) cumsum...
    (W_rank(:,9)) zeros(size(YI,1),2)];
P_ret = [cumsum(P_rank(:,6)) cumsum(P_rank(:,8)) cumsum(P_rank(:,3)) cumsum...
    (P_rank(:,9)) zeros(size(YI,1),2)];
T_ret(:,5) = (total_water*ones(size(YI,1),1) - cumsum(T_rank(:,4).*T_rank...
    (:,3)))./(total_acres*ones(size(YI,1),1) - cumsum(T_rank(:,3)));
Z_ret(:,5) = (total_water*ones(size(YI,1),1) - cumsum(Z_rank(:,4).*Z_rank...
    (:,3)))./(total_acres*ones(size(YI,1),1) - cumsum(Z_rank(:,3)));
S_ret(:,5) = (total_water*ones(size(YI,1),1) - cumsum(S_rank(:,4).*S_rank...
    (:,3)))./(total_acres*ones(size(YI,1),1) - cumsum(S_rank(:,3)));
W_ret(:,5) = (total_water*ones(size(YI,1),1) - cumsum(W_rank(:,4).*W_rank...
    (:,3)))./(total_acres*ones(size(YI,1),1) - cumsum(W_rank(:,3)));
P_ret(:,5) = (total_water*ones(size(YI,1),1) - cumsum(P_rank(:,4).*P_rank...
    (:,3)))./(total_acres*ones(size(YI,1),1) - cumsum(P_rank(:,3)));
T_ret(:,6) = (total_sd*ones(size(YI,1),1) - cumsum(T_rank(:,7).*T_rank(:,3)...
    ))./(total_acres*ones(size(YI,1),1) - cumsum(T_rank(:,3)));
```

```
Z_ret(:,6) = (total_sd*ones(size(YI,1),1) - cumsum(Z_rank(:,7).*Z_rank(:,3)...
    ))./(total_acres*ones(size(YI,1),1) - cumsum(Z_rank(:,3)));
S_ret(:,6) = (total_sd*ones(size(YI,1),1) - cumsum(S_rank(:,7).*S_rank(:,3)...
    ))./(total_acres*ones(size(YI,1),1) - cumsum(S_rank(:,3)));
W_ret(:,6) = (total_sd*ones(size(YI,1),1) - cumsum(W_rank(:,7).*W_rank(:,3)...
    ))./(total_acres*ones(size(YI,1),1) - cumsum(W_rank(:,3)));
P_ret(:,6) = (total_sd*ones(size(YI,1),1) - cumsum(P_rank(:,7).*P_rank(:,3)...
    ))./(total_acres*ones(size(YI,1),1) - cumsum(P_rank(:,3)));


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Trading scenarios w/ increasing regulation %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
perc_ret = (0:0.01:1)';  %percentage of retired permits
steps_ret = length(perc_ret);

%Trading, 1:1
tic
vol_11 = zeros(steps_ret,1); %volume of transacted permits (acres)
acr_11 = zeros(steps_ret,1); %acres retired
Esdr_11 = zeros(steps_ret,1); %expected stream depletion change (SDF * area...
    )
Asdr_11 = zeros(steps_ret,1); %actual stream depletion change (SD/ac * area...
    )
dyd_11 = zeros(steps_ret,1); %total increase of yield (bu/ac * ac)
wat_11 = zeros(steps_ret,1);
sda_11 = zeros(steps_ret,1);

for kk = 1:steps_ret
    ret_11 = [YI(:,1:2), perc_ret(kk)*YI(:,3), YI(:,4), YI(:,7)];
    wi_11 = [YI(:,1:2), (1 - perc_ret(kk))*YI(:,3), YI(:,4), YI(:,7)];
    wo_11 = [YD; ret_11];

    fields_irr = size(wi_11,1);
    fields_dry = size(wo_11,1);

```

```
%Preallocate and find effective bid
eff_bid_11 = zeros(fields_irr,fields_dry);  %effective bid between each...
    buyer and seller, weighted by SDF

for i = 1:fields_irr     %sellers
    for j = 1:fields_dry %buyers
        if wo_11(j,3) > 0
            %if there is positive acreage, there is a demand to buy.
            %otherwise, eff_bid = 0.
            eff_bid_11(i,j) = max(wo_11(j,1) - wi_11(i,1),0);
            %the difference between the yield values
        end
    end
end

[ranked_11 index_11] = sortrows(reshape(eff_bid_11,[],1),-1);
%properties of trades
%(1) total increase in yields
%(2) expected change in SD
%(3) actual change in SD
%(4) acres sold
%(5) acres bought
%(6) to track change in avg water use
trades_11 = zeros(size(index_11,1),7);

%tracks acreage
purch_11 = zeros(fields_dry,1);
sold_11 = zeros(fields_irr,1);

for i = 1:length(index_11)
    if ranked_11(i) > 0
        seller_index = 1 + rem(index_11(i) + fields_irr - 1, fields_irr...
            );
        buyer_index = ceil(index_11(i)/fields_irr);
        %seller's constraint
        S_con_11 = (wi_11(seller_index,3)-sold_11(seller_index,1));
```

```
            %buyer's constraint
            B_con_11 = (wo_11(buyer_index,3)-purch_11(buyer_index,1));
            %trade max acres between constraints
            const_11 = min([S_con_11 B_con_11]);
            trades_11(i,4) = const_11;
            trades_11(i,5) = const_11;
            trades_11(i,6) = wo_11(buyer_index,4)*trades_11(i,5) - wi_11(...
               seller_index,4)*trades_11(i,4);
            trades_11(i,7) = wo_11(buyer_index,5)*trades_11(i,5) - wi_11(...
               seller_index,5)*trades_11(i,4);
            trades_11(i,1) = wo_11(buyer_index,1)*trades_11(i,5) - wi_11(...
               seller_index,1)*trades_11(i,4);
            trades_11(i,2) = wo_11(buyer_index,2)*trades_11(i,5) - wi_11(...
               seller_index,2)*trades_11(i,4);
            trades_11(i,3) = wo_11(buyer_index,5)*trades_11(i,5) - wi_11(...
               seller_index,5)*trades_11(i,4);
            %update buyer
            purch_11(buyer_index,1) = purch_11(buyer_index,1) + trades_11(i...
               ,5);
            %update seller
            sold_11(seller_index,1) = sold_11(seller_index,1) + trades_11(i...
               ,4);
        end
    end
    %for final output
    acr_11(kk,1) = sum(ret_11(:,3));
    dyd_11(kk,1) = sum(ret_11(:,1).*ret_11(:,3)) - sum(trades_11(:,1));
    Esdr_11(kk,1) = wtd_pump*(sum(ret_11(:,2).*ret_11(:,3)) - sum(trades_11...
       (:,2)));
    Asdr_11(kk,1) = sum(ret_11(:,5).*ret_11(:,3)) - sum(trades_11(:,3));
    vol_11(kk,1:2) = sum(trades_11(:,4:5));
    wat_11(kk,1) = (sum(wi_11(:,3).*wi_11(:,4)) + sum(trades_11(:,6)))/sum(...
       wi_11(:,3));
    sda_11(kk,1) = (sum(wi_11(:,3).*wi_11(:,5)) + sum(trades_11(:,7)))/sum(...
       wi_11(:,3));
end
```

```
toc

%SDF trading: bi-directional
tic
vol_2d = zeros(steps_ret,2); %volume of acres bought, volume of acres sold
acr_2d = zeros(steps_ret,1); %acres retired
Esdr_2d = zeros(steps_ret,1); %expected stream depletion reduction (SDF * ...
    area)
Asdr_2d = zeros(steps_ret,1); %actual stream depletion reduction (SD/ac * ...
    area)
dyd_2d = zeros(steps_ret,1); %total decrease of yield (bu/ac * ac)
wat_2d = zeros(steps_ret,1);
sda_2d = zeros(steps_ret,1);

for kk = 1:steps_ret
    ret_2d = [YI(:,1:2), perc_ret(kk)*YI(:,3), YI(:,4), YI(:,7)];
    wi_2d = [YI(:,1:2), (1 - perc_ret(kk))*YI(:,3), YI(:,4), YI(:,7)];
    wo_2d = [YD; ret_2d];

    fields_irr = size(wi_2d,1);
    fields_dry = size(wo_2d,1);

    %Preallocate and find effective bid
    eff_bid_2d = zeros(fields_irr,fields_dry);  %effective bid between each...
         buyer and seller, weighted by SDF

    for i = 1:fields_irr     %sellers
        for j = 1:fields_dry %buyers
            if wo_2d(j,3) > 0
                %if there is positive acreage, there is a demand to buy.
                %otherwise, eff_bid = 0.
                eff_bid_2d(i,j) = max(wo_2d(j,1) - wi_2d(i,1)*wo_2d(j,2)/...
                    wi_2d(i,2),0);
                %related by y = mx + b, where m is the seller's sdf/yd, b ...
                    is the
```

```
            %y-intercept for the buyer using that seller's sdf/yd. then...
                 set y =
            %0 and solve for x, the effective bid.
        end
    end
end

[ranked_2d index_2d] = sortrows(reshape(eff_bid_2d,[],1),-1);
%properties of trades
%(1) total increase in yields
%(2) expected change in SD
%(3) actual change in SD
%(4) acres sold
%(5) acres bought
trades_2d = zeros(size(index_2d,1),7);

%tracks acreage
purch_2d = zeros(fields_dry,1);
sold_2d = zeros(fields_irr,1);

for i = 1:length(index_2d)
    if ranked_2d(i) > 0
        seller_index = 1 + rem(index_2d(i) + fields_irr - 1, fields_irr...
            );
        buyer_index = ceil(index_2d(i)/fields_irr);
        %seller's constraint
        S_con = (wi_2d(seller_index,3)-sold_2d(seller_index,1))*wi_2d(...
            seller_index,2);
        %buyer's constraint
        B_con = (wo_2d(buyer_index,3)-purch_2d(buyer_index,1))*wo_2d(...
            buyer_index,2);
        %trade max acres between constraints
        [const_2d IX] = min([S_con B_con]);
        if IX == 1
            %S_con binds
```

```
                trades_2d(i,4) = wi_2d(seller_index,3)-sold_2d(seller_index...
                    ,1);
                trades_2d(i,5) = const_2d/wo_2d(buyer_index,2);
            else
                %B_con binds
                trades_2d(i,4) = const_2d/wi_2d(seller_index,2);
                trades_2d(i,5) = wo_2d(buyer_index,3)-purch_2d(buyer_index...
                    ,1);
            end
            trades_2d(i,6) = wo_2d(buyer_index,4)*trades_2d(i,5) - wi_2d(...
                seller_index,4)*trades_2d(i,4);
            trades_2d(i,7) = wo_2d(buyer_index,5)*trades_2d(i,5) - wi_2d(...
                seller_index,5)*trades_2d(i,4);
            trades_2d(i,1) = wo_2d(buyer_index,1)*trades_2d(i,5) - wi_2d(...
                seller_index,1)*trades_2d(i,4);
            trades_2d(i,2) = wo_2d(buyer_index,2)*trades_2d(i,5) - wi_2d(...
                seller_index,2)*trades_2d(i,4);
            trades_2d(i,3) = wo_2d(buyer_index,5)*trades_2d(i,5) - wi_2d(...
                seller_index,5)*trades_2d(i,4);
            %update buyer
            purch_2d(buyer_index,1) = purch_2d(buyer_index,1) + trades_2d(i...
                ,5);
            %update seller
            sold_2d(seller_index,1) = sold_2d(seller_index,1) + trades_2d(i...
                ,4);
        end
    end
    %for final output
    acr_2d(kk,1) = sum(ret_2d(:,3));
    dyd_2d(kk,1) = sum(ret_2d(:,1).*ret_2d(:,3)) - sum(trades_2d(:,1));
    Esdr_2d(kk,1) = wtd_pump*(sum(ret_2d(:,2).*ret_2d(:,3)) - sum(trades_2d...
        (:,2)));
    Asdr_2d(kk,1) = sum(ret_2d(:,5).*ret_2d(:,3)) - sum(trades_2d(:,3));
    vol_2d(kk,1:2) = sum(trades_2d(:,4:5));
    wat_2d(kk,1) = (sum(wi_2d(:,3).*wi_2d(:,4)) + sum(trades_2d(:,6)))/(sum...
        (wi_2d(:,3)) + sum(trades_2d(:,5)) - sum(trades_2d(:,4)));
```

```
    sda_2d(kk,1) = (sum(wi_2d(:,3).*wi_2d(:,5)) + sum(trades_2d(:,7)))/(sum...
        (wi_2d(:,3)) + sum(trades_2d(:,5)) - sum(trades_2d(:,4)));
end
toc

%Trading, 1d
tic
vol_1d = zeros(steps_ret,2); %volume of acres bought, volume of acres sold
acr_1d = zeros(steps_ret,1); %acres retired
Esdr_1d = zeros(steps_ret,1); %expected stream depletion reduction (SDF * ...
    area)
Asdr_1d = zeros(steps_ret,1); %actual stream depletion reduction (SD/ac * ...
    area)
dyd_1d = zeros(steps_ret,1); %total decrease of yield (bu/ac * ac)
wat_1d = zeros(steps_ret,1);
sda_1d = zeros(steps_ret,1);

for kk = 1:steps_ret
    ret_1d = [YI(:,1:2), perc_ret(kk)*YI(:,3), YI(:,4), YI(:,7)];
    wi_1d = [YI(:,1:2), (1 - perc_ret(kk))*YI(:,3), YI(:,4), YI(:,7)];
    wo_1d = [YD; ret_1d];

    fields_irr = size(wi_1d,1);
    fields_dry = size(wo_1d,1);

    %Preallocate and find effective bid
    eff_bid_1d = zeros(fields_irr,fields_dry);    %effective bid between ...
        each buyer and seller, weighted by SDF
    bid_type = zeros(fields_irr,fields_dry);      %zero for 1:1 trade, 1 if...
         discounted

    for i = 1:fields_irr     %sellers
        for j = 1:fields_dry %buyers
            if wo_1d(j,3) > 0
                %if there is positive acreage, there is a demand to buy.
                %otherwise, eff_bid = 0.
```

```
                if wi_1d(i,2) ≥ wo_1d(j,2)
                    %SDF of seller is less than SDF of buyer, 1:1 trade
                    eff_bid_1d(i,j) = max(0, wo_1d(j,1) - wi_1d(i,1));
                else
                    bid_type(i,j) = 1;
                    eff_bid_1d(i,j) = max(wo_1d(j,1) - wi_1d(i,1)*wo_1d(j...
                        ,2)/wi_1d(i,2),0);
                    %related by y = mx + b, where m is the seller's sdf/yd,...
                         b is the
                    %y-intercept for the buyer using that seller's sdf/yd. ...
                        then set y =
                    %0 and solve for x, the effective bid.
                end
            end
        end
    end

    [ranked_1d index_1d] = sortrows(reshape(eff_bid_1d,[],1),-1);
    %properties of trades
    %(1) total increase in yields
    %(2) expected change in SD
    %(3) actual change in SD
    %(4) acres sold
    %(5) acres bought
    trades_1d = zeros(size(index_1d,1),7);

    %tracks acreage
    purch_1d = zeros(fields_dry,1);
    sold_1d = zeros(fields_irr,1);

    for i = 1:length(index_1d)
        if ranked_1d(i) > 0
            buyer_index = ceil(index_1d(i)/fields_irr);
            seller_index = 1 + rem(index_1d(i) + fields_irr - 1, fields_irr...
                );
            if bid_type(index_1d(i)) == 0
```

```
            %seller's constraint
            S_con_1d = (wi_1d(seller_index,3)-sold_1d(seller_index,1));
            %buyer's constraint
            B_con_1d = (wo_1d(buyer_index,3)-purch_1d(buyer_index,1));
            const_1d = min([S_con_1d B_con_1d]);
            trades_1d(i,4) = const_1d;
            trades_1d(i,5) = const_1d;
        else
            %seller's constraint
            S_con_1d = (wi_1d(seller_index,3)-sold_1d(seller_index,1))*...
                wi_1d(seller_index,2);
            %buyer's constraint
            B_con_1d = (wo_1d(buyer_index,3)-purch_1d(buyer_index,1))*...
                wo_1d(buyer_index,2);
            %trade max acres between constraints
            [const_1d IX] = min([S_con_1d B_con_1d]);
            if IX == 1
                %S_con binds
                trades_1d(i,4) = wi_1d(seller_index,3)-sold_1d(...
                    seller_index,1);
                trades_1d(i,5) = const_1d/wo_1d(buyer_index,2);
            else
                %B_con binds
                trades_1d(i,4) = const_1d/wi_1d(seller_index,2);
                trades_1d(i,5) = wo_1d(buyer_index,3)-purch_1d(...
                    buyer_index,1);
            end
        end
        trades_1d(i,6) = wo_1d(buyer_index,4)*trades_1d(i,5) - wi_1d(...
            seller_index,4)*trades_1d(i,4);
        trades_1d(i,7) = wo_1d(buyer_index,5)*trades_1d(i,5) - wi_1d(...
            seller_index,5)*trades_1d(i,4);
        trades_1d(i,1) = wo_1d(buyer_index,1)*trades_1d(i,5) - wi_1d(...
            seller_index,1)*trades_1d(i,4);
        trades_1d(i,2) = wo_1d(buyer_index,2)*trades_1d(i,5) - wi_1d(...
            seller_index,2)*trades_1d(i,4);
```

```
            trades_1d(i,3) = wo_1d(buyer_index,5)*trades_1d(i,5) - wi_1d(...
                seller_index,5)*trades_1d(i,4);
            %update buyer
            purch_1d(buyer_index,1) = purch_1d(buyer_index,1) + trades_1d(i...
                ,5);
            %update seller
            sold_1d(seller_index,1) = sold_1d(seller_index,1) + trades_1d(i...
                ,4);
        end
    end
    %for final output
    acr_1d(kk,1) = sum(ret_1d(:,3));
    dyd_1d(kk,1) = sum(ret_1d(:,1).*ret_1d(:,3)) - sum(trades_1d(:,1));
    Esdr_1d(kk,1) = wtd_pump*(sum(ret_1d(:,2).*ret_1d(:,3)) - sum(trades_1d...
        (:,2)));
    Asdr_1d(kk,1) = sum(ret_1d(:,5).*ret_1d(:,3)) - sum(trades_1d(:,3));
    vol_1d(kk,1:2) = sum(trades_1d(:,4:5));
    wat_1d(kk,1) = (sum(wi_1d(:,3).*wi_1d(:,4)) + sum(trades_1d(:,6)))/(sum...
        (wi_1d(:,3)) + sum(trades_1d(:,5)) - sum(trades_1d(:,4)));
    sda_1d(kk,1) = (sum(wi_1d(:,3).*wi_1d(:,5)) + sum(trades_1d(:,7)))/(sum...
        (wi_1d(:,3)) + sum(trades_1d(:,5)) - sum(trades_1d(:,4)));
end
toc

%%%%%%%%%%%
% FIGURES %
%%%%%%%%%%%
%set(0,'DefaultAxesColorOrder',[0 0 0],'DefaultAxesLineStyleOrder...
    ','-|--|:|-.')
set(0,'DefaultAxesLineStyleOrder','-|--|-.')
set(0,'DefaultAxesColorOrder',[0 0 0])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Dryland/ irrigated properties %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
formspec1 = 'TPNRD_properties';
```

```
fnam3 = sprintf(formspec1);
h3 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], 'Visible', ...
    'off');
subplot(1,2,1);
%h4 = plot(YI(:,1),100*YI(:,2),YI(:,3)/50,'ok','LineWidth',2);
%set (h4,'FontSize',20)
h4 = scatter(YI(:,1),100*YI(:,2),YI(:,3)/50,'k','LineWidth',2);
set(gca,'FontSize',20)
%axis([250 450 0 16])
ylabel('\fontsize{24} Stream depletion factor (%)')
xlabel('\fontsize{24} Profitability of irrigation ($/ac)')
title('\fontsize{28} Irrigated Fields')
subplot(1,2,2)
h5 = scatter(XR(:,1),100*XR(:,2),XR(:,3)/50,'k','LineWidth',2);
set(gca,'FontSize',20)
%axis([250 450 0 16])
ylabel('\fontsize{24} Stream depletion factor (%)')
xlabel('\fontsize{24} Profitability of irrigation ($/ac)')
title('\fontsize{28} Dryland Fields')
print(h3,fnam3,'-depsc')

%%%%%%%%%%%%%%%%%%
% Policy analysis %
%%%%%%%%%%%%%%%%%%
formspec1 = 'TPNRD_micro';
fnam1 = sprintf(formspec1);
h1 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], 'Visible', ...
    'off');
r1 = plot(T_ret(1:4:end,2)/12,T_ret(1:4:end,1)/(10^6),'--x',S_ret(:,2)/12,...
    S_ret(:,1)/(10^6),':',Z_ret(1:6:end,2)/12,Z_ret(1:6:end,1)/(10^6),'--o'...
    ,P_ret(:,2)/12,P_ret(:,1)/(10^6),'-',Asdr_11(1:4:end,:)/12,dyd_11(1:4...
    :end,:)/(10^6),'-.s',Asdr_1d/12,dyd_1d/(10^6),'-.',Asdr_2d/12,dyd_2d...
    /(10^6),'--');
r2 = legend('Land tax','SDF tax','Zoning','Depletion tax','Trading, one-to-...
    one','Trading, unidirectional','Trading, bidirectional','Location','...
    Northwest');
```

```
set(r1,'LineWidth',2)
set(r2,'FontSize',16)
set(gca,'FontSize',20)
xlim([0 (4.6*10^4)])
title({'\fontsize{28} Comparison of Policies to Increase Streamflow'})
xlabel('\fontsize{24} Total increase in streamflow (ac-ft)')        %...
    abatement
ylabel('\fontsize{24} Total reduction of profits ($M)')
print(h1,fnam1,'-depsc')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Irrigated land and streamflow %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
formspec3 = 'TPNRD_area';
fnam3 = sprintf(formspec3);
h3 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], 'Visible', ...
    'off');
r1 = plot(T_ret(1:4:end,3),T_ret(1:4:end,2)/12,'--x',S_ret(:,3),S_ret(:,2)...
    /12,':',Z_ret(1:4:end,3),Z_ret(1:4:end,2)/12,'--o',P_ret(:,3),P_ret...
    (:,2)/12,'-',acr_11(1:4:end,:),Asdr_11(1:4:end,:)/12,'-.s',acr_1d,...
    Asdr_1d/12,'-.',acr_2d,Asdr_2d/12,'--');
r2 = legend('Land tax','SDF tax','Zoning','Depletion tax','Trading, one-to-...
    one','Trading, unidirectional','Trading, bidirectional','Location','...
    Northwest');
set(r1,'LineWidth',2)
set(r2,'FontSize',16)
set(gca,'FontSize',20)
title({'\fontsize{28} Reduction of Stream Depletion with Area'})
xlabel('\fontsize{24} Total reduction of irrigated land (ac)')   %permits ...
    retired
ylabel('\fontsize{24} Total increase in streamflow (ac-ft)')        %...
    abatement
print(h3,fnam3,'-depsc')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Average water usage changes %
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
formspec1 = 'TPNRD_water4';
fnam3 = sprintf(formspec1);
h3 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], 'Visible', ...
    'off');
r1 = plot(T_ret(:,2)/12,T_ret(:,5),W_ret(:,2)/12,W_ret(:,5),S_ret(:,2)/12,...
    S_ret(:,5),P_ret(:,2)/12,P_ret(:,5),Z_ret(:,2)/12,Z_ret(:,5),Asdr_11...
    /12,wat_11,'--',Asdr_2d/12,wat_2d,'--',Asdr_1d/12,wat_1d,'--'); %...
    abatement vs avg water usage
axis([0 total_sd/12 14.5 16])
ylabel('\fontsize{16} Average water usage (in)')
xlabel('\fontsize{16} Total increase in streamflow (ac-ft)')
title('\fontsize{20} Resulting Changes in Water Usage')
r2 = legend('Land tax','Water tax','SDF tax','Pigouvian tax','Zoning','...
    Trading, 1:1','Trading, bidirectional','Trading, unidirectional','...
    Location','Northwest');
set(r1,'LineWidth',1)
set(r2,'FontSize',14)
print(h3,fnam3,'-depsc')

formspec1 = 'TPNRD_watland4';
fnam3 = sprintf(formspec1);
h3 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], 'Visible', ...
    'off');
r1 = plot(T_ret(:,3),T_ret(:,5),W_ret(:,3),W_ret(:,5),S_ret(:,3),S_ret(:,5)...
    ,P_ret(:,3),P_ret(:,5),Z_ret(:,3),Z_ret(:,5),acr_11,wat_11,'--',acr_2d,...
    wat_2d,'--',acr_1d,wat_1d,'--'); %abatement vs avg water usage
axis([0 total_acres 14.5 16])
ylabel('\fontsize{16} Average water usage (in)')
xlabel('\fontsize{16} Total reduction of irrigated land (ac)')
title('\fontsize{20} Resulting Changes in Water Usage')
r2 = legend('Land tax','Water tax','SDF tax','Pigouvian tax','Zoning','...
    Trading, 1:1','Trading, bidirectional','Trading, unidirectional','...
    Location','Northwest');
set(r1,'LineWidth',1)
set(r2,'FontSize',14)
```

```
print(h3,fnam3,'-depsc')


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Average stream depletion changes %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
formspec1 = 'TPNRD_sdac4';
fnam3 = sprintf(formspec1);
h3 = figure('PaperUnits','inches','PaperPosition',[.5 .5 12 8], 'Visible', ...
    'off');
r1 = plot(T_ret(:,2)/12,T_ret(:,6),W_ret(:,2)/12,W_ret(:,6),S_ret(:,2)/12,...
    S_ret(:,6),P_ret(:,2)/12,P_ret(:,6),Z_ret(:,2)/12,Z_ret(:,6),Asdr_11...
    /12,sda_11,'--',Asdr_2d/12,sda_2d,'--',Asdr_1d/12,sda_1d,'--'); %...
    abatement vs avg water usage
ylim([0 9])
xlim([0 4.5*10^4])
ylabel('\fontsize{16} Average stream depletion per acre (ac-in/ac)')
xlabel('\fontsize{16} Total increase in streamflow (ac-ft)')
title('\fontsize{20} Resulting Changes in Water Usage')
r2 = legend('Land tax','Water tax','SDF tax','Pigouvian tax','Zoning','...
    Trading, 1:1','Trading, bidirectional','Trading, unidirectional','...
    Location','Northeast');
set(r1,'LineWidth',1)
set(r2,'FontSize',14)
print(h3,fnam3,'-depsc')
```

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